FLASY 2018

Search for lepton flavour violation with the ATLAS detector

Matteo Bedognetti *(Nikhef Institute, Radboud University of Nijmegen)*
On behalf of the ATLAS collaboration

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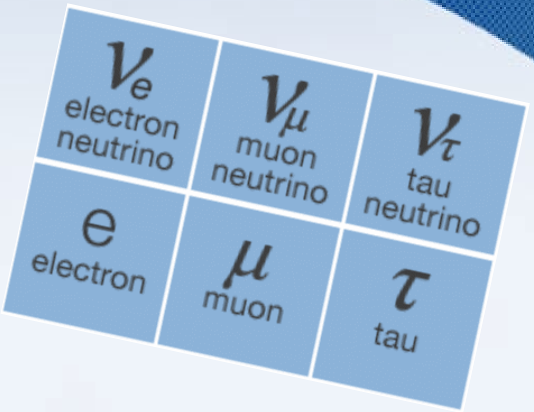
Radboud Universiteit Nijmegen

Nikhef

Overview



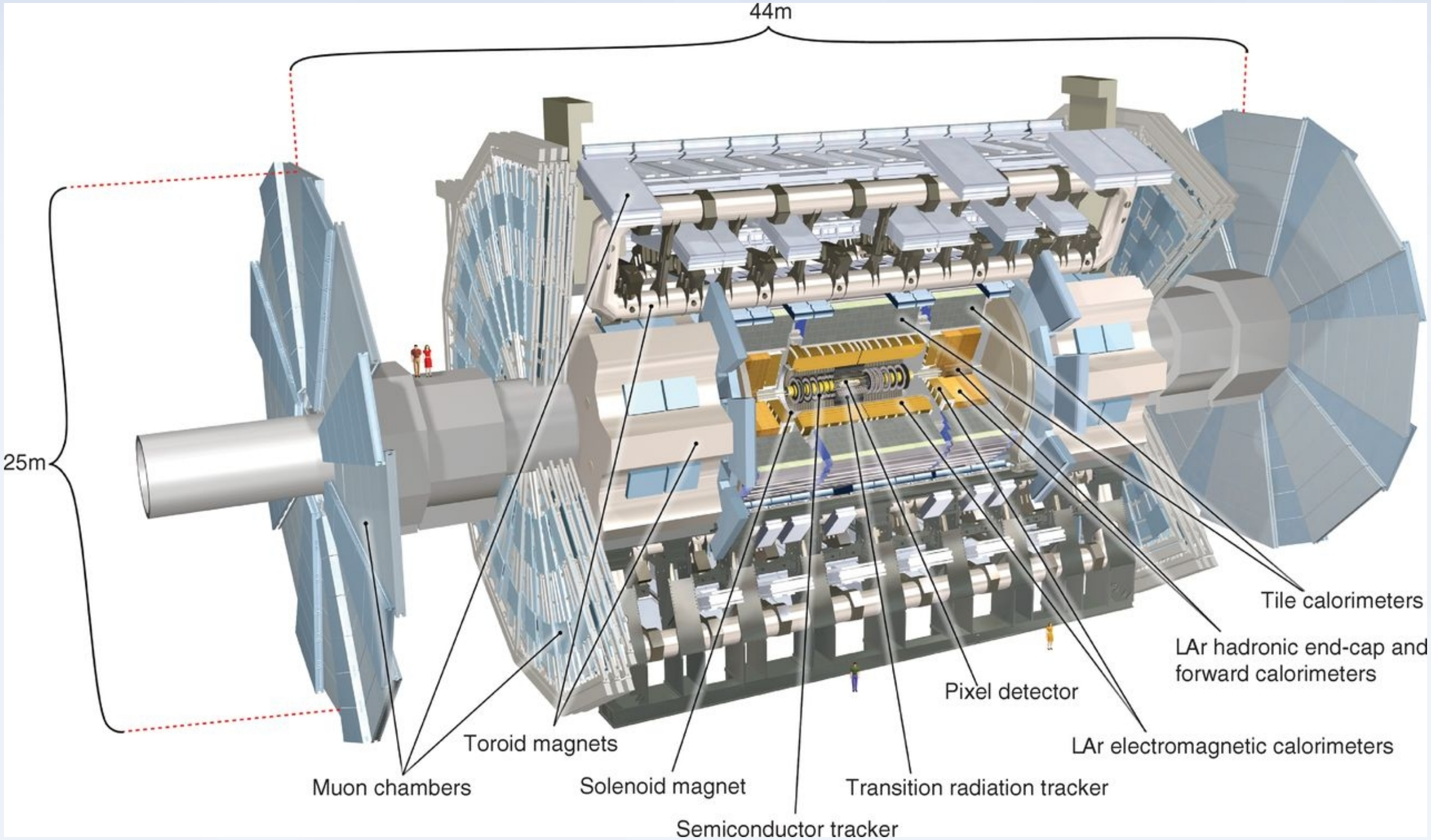
- Leptons come in 3 flavours in the Standard Model
- They can change flavour: PMNS allows neutrino transition

- Lepton flavour is conserved in the charged sector
- Impact of neutrino mixing is strongly suppressed due to small ν masses

- BSM scenarios foresee branching ratios observable at the LHC (Z’, 2HDM, composite H, SUSY)
- Any observation is a discovery!

- LFV searches at ATLAS focus on signatures in decays of p-p collision products
- Standard Model bosons (H, Z)
- Exotic massive states (Z’, …)
- τ-leptons

The ATLAS experiment



- **High precision tracking system**
  silicon pixels, strips and transition radiation tracker, down to 3cm from beam axis
- **Two calorimeters**
  EM: LAr, Hadronic: scintillating tiles and LAr end-caps
- **Muon spectrometer**
  drift tubes, multiwire chambers, RPC
- **Two magnet systems**
  solenoid and toroid
- **Powerful trigger/DAQ system**

LFV in Higgs boson decays

arXiv:1508.03372
arXiv:1604.07730

- Exploring LFV couplings is part of characterizing H (125 GeV Higgs)
- Possible channels: $H \to e\mu$, $H \to \tau e$ and $H \to \tau\mu$
- ATLAS published no result for $H \to e\mu$
  (from indirect search $\mu \to e\gamma$, Br is limited to 10^{-8}, within assumptions)
- For $H \to \tau e$ and $H \to \tau\mu$, results dominate over indirect searches
- Latest results employ 20.3 fb^{-1} of 2012 data with **$\sqrt{s}$ = 8 TeV**
- Searches explored **hadronic** and **leptonic** τ decays

Br($\mu \to e\gamma$) < 4.2x10-13
@ 90% C.L. (MEG 2016)

LFV in Higgs boson decays: hadronic-τ

arXiv:1508.03372
arXiv:1604.07730

$H\rightarrow\tau^{had}e$ & $H\rightarrow\tau^{had}\mu$

- Energetic e or μ
- Energetic τ aligned with medium E_T^{miss} (neutrino)
- Events with further energetic electrons / muons are rejected

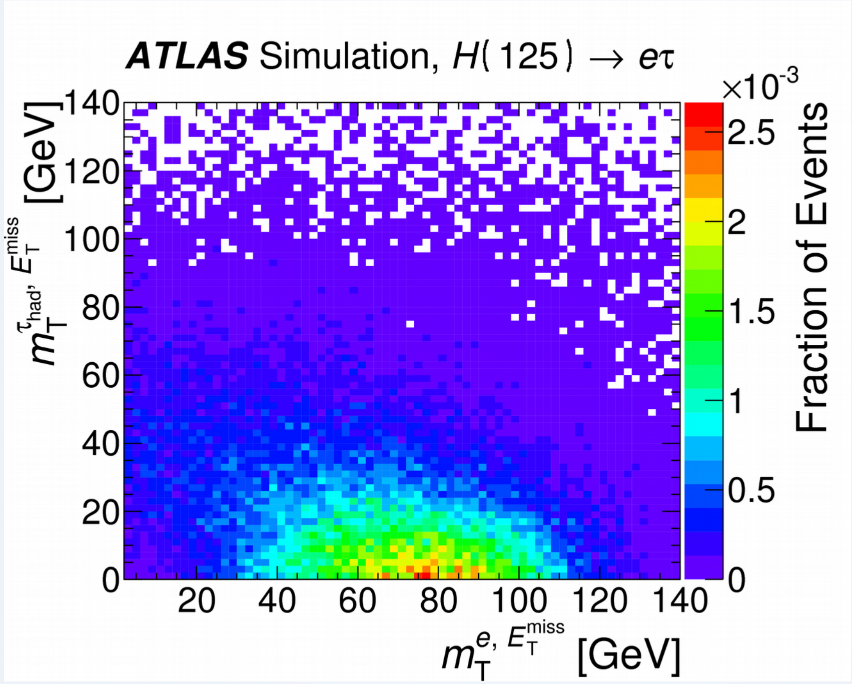
- Hadronic τ are identified with a multivariate classifier based on boosted decision trees
- Contamination from faked τ is reduced
  - rejecting low-energetic e/μ overlap on τ
  - Requiring high transverse momentum for τ (>45 GeV)

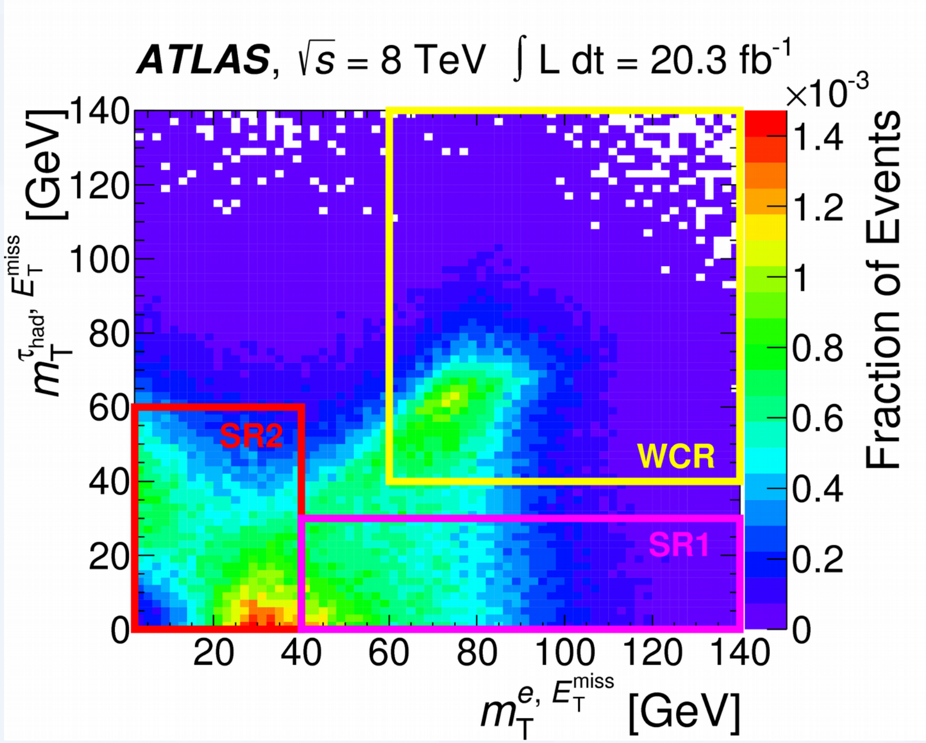
- B-tagged jets are vetoed

LFV in Higgs boson decays: hadronic-τ

arXiv:1508.03372
arXiv:1604.07730

- Much in common with $H\rightarrow\tau\tau$ search [arXiv:1501.04943]
- Backgrounds: $Z\rightarrow\tau\tau$, $Z\rightarrow\mu\mu(ee)$, top, W+jet, t, $t\bar{t}$, $H\rightarrow\tau\tau$
- Multi-jet and W+jet BKG reduced through $|\eta(\tau) - \eta(e/\mu)|<2$ and B-tagged jet rejection
- Two Signal Regions are defined on the basis of $M_T(e/\mu, E_T^{miss})$ vs. $M_T(\tau, E_T^{miss})$
- Control regions are defined for W+jet, top





LFV in Higgs boson decays: hadronic-τ

arXiv:1508.03372
arXiv:1604.07730

- **Background Characterization:**
- $Z/\gamma^*\to\tau\tau$ obtained by "embedding" simulated τ into real $Z/\gamma^*\to\mu\mu$ events
- Multi-jet are taken from events containing 2 leptons of the same charge:

$$N_{\mathrm{OS}}^{\mathrm{bkg}} = r_{\mathrm{QCD}} \cdot N_{\mathrm{SS}}^{\mathrm{data}} + \sum_{\mathrm{bkg}-i} N_{\mathrm{OS-SS}}^{\mathrm{bkg}-i},$$

SS: Same Sign (charge)
OS: Opposite Sign (charge)

- r_{QCD} is a data-driven correction to describe residual SS-OS difference in Multi-jet
- The remaining backgrounds are simulation, corrected for their contribution to SS

- **Missing Mass Calculator** determines most likely invariant mass of the τ-e/μ system uses constraint of τ mass and decay kinematics to best include E_T^{miss}
- **Simultaneous max-likelyhood binned fit on MMC (and event yield on CRs)**

LFV in Higgs boson decays: hadronic-τ

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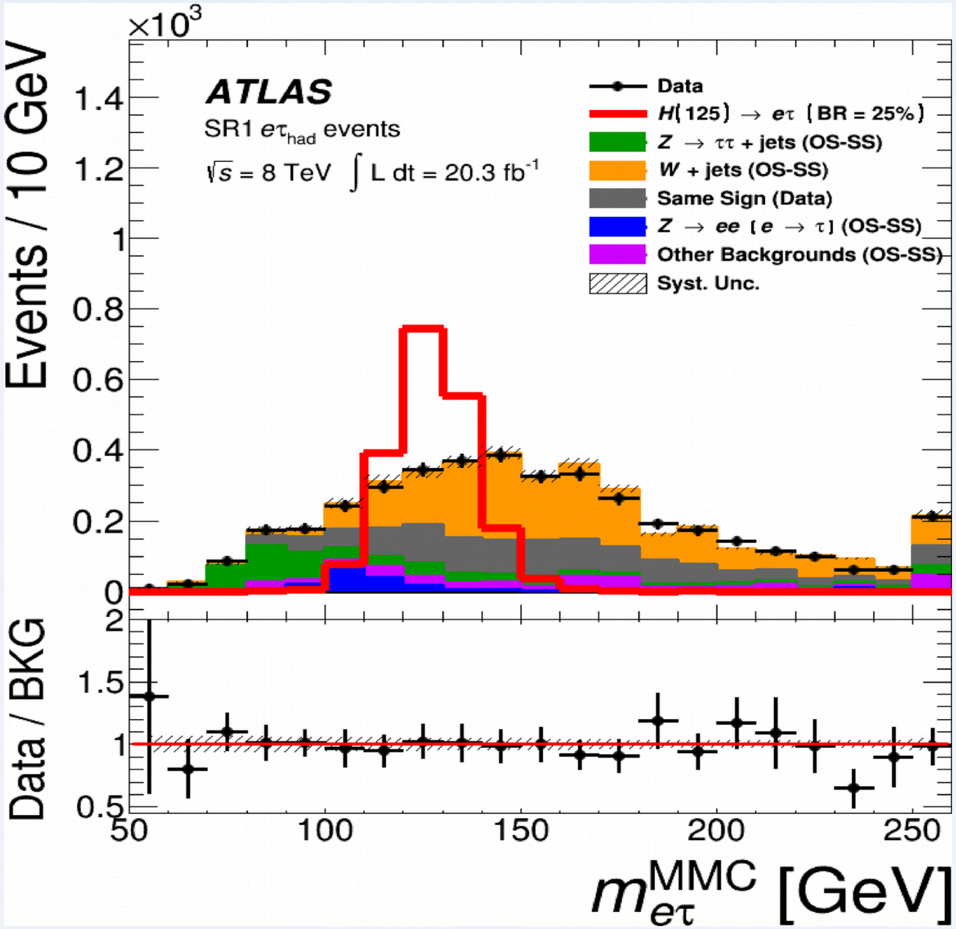
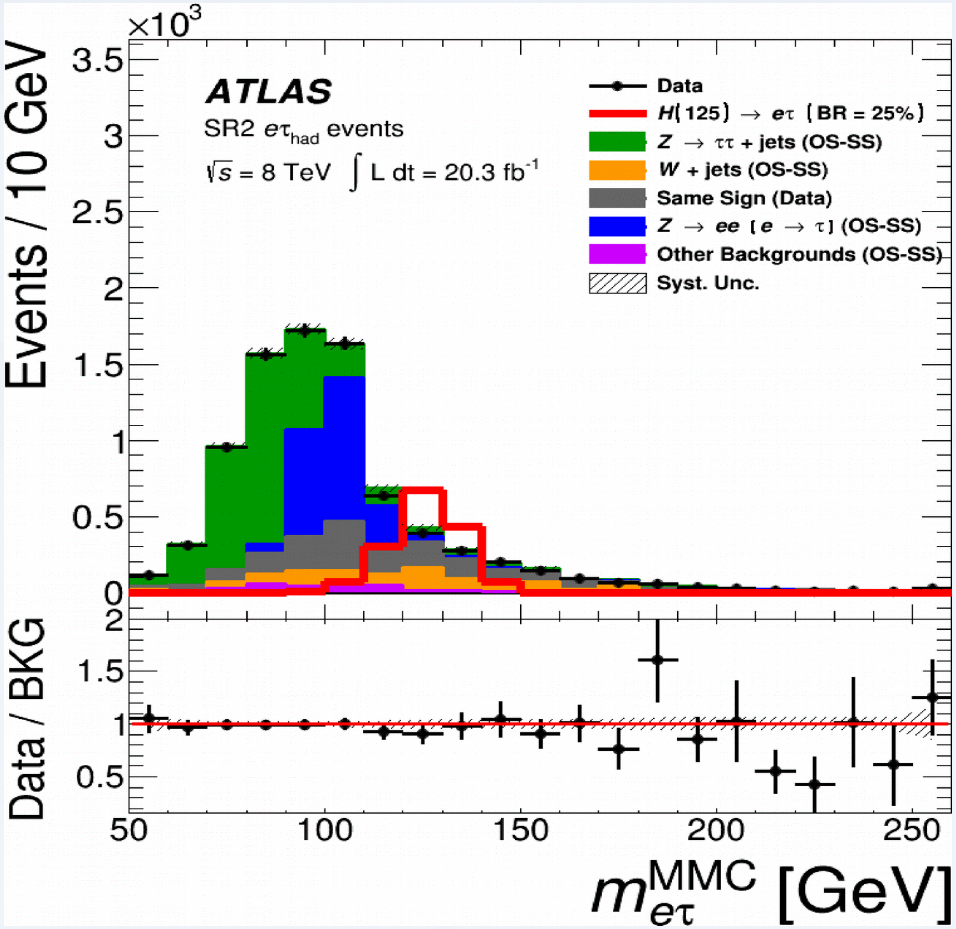




LFV in Higgs boson decays: leptonic-τ

arXiv:1604.07730

$H\to\tau^{lep}e$ & $H\to\tau^{lep}\mu$

- Analysis is based on the symmetry in SM of sources of e and μ
- Focus on events with oppositely charged e and μ
- Events divided in **eμ** and **μe** (more energetic lepton first)

- Signal Regions defined through e/μ kinematics:
  - angular separation with respect to E_T^{miss} (E_T^{miss} must be close to the softer lepton)
  - Angular and P_T relations between leptons (back-to-back, energy gap due to neutrinos)
- Two exclusive Signal Regions: **with-Jets** and **no-Jets** in the central region ($|\eta| < 2.4$)

LFV in Higgs boson decays: leptonic-τ

arXiv:1604.07730

$H \to \tau^{lep} e$ & $H \to \tau^{lep} \mu$

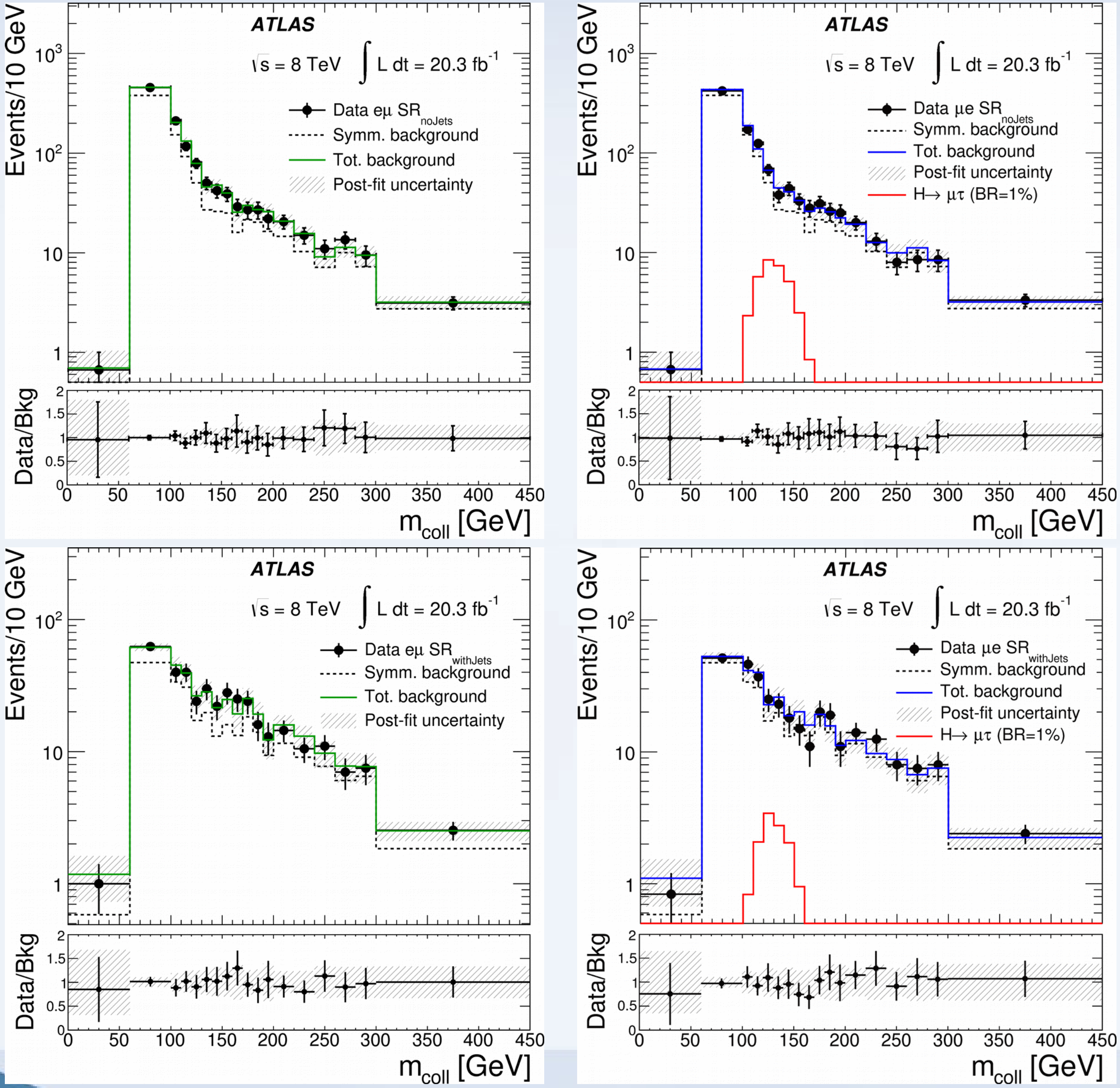
- Backgrounds entirely estimated from **data:**
- eμ and μe regions expected to be equally populated in SM
- To first approximation "symmetric background" for eμ is μe and vice versa (common fit)
- Asymmetry correction need be added for
  - Misidentification and non-prompt leptons (different for e and μ)
  - Trigger and reconstruction inefficiency for sub-leading lepton
- Final discriminant is Collinear Mass

$$m_{\text{coll}} = \sqrt{2 p_{\text{T}}^{\ell_1} \left(p_{\text{T}}^{\ell_2} + E_{\text{T}}^{\text{miss}} \right) (\cosh \Delta\eta - \cos \Delta\phi)}.$$

- More involved estimates (MMC) were shown not to improve sensitivity

LFV in Higgs boson decays: leptonic-τ

arXiv:1604.07730

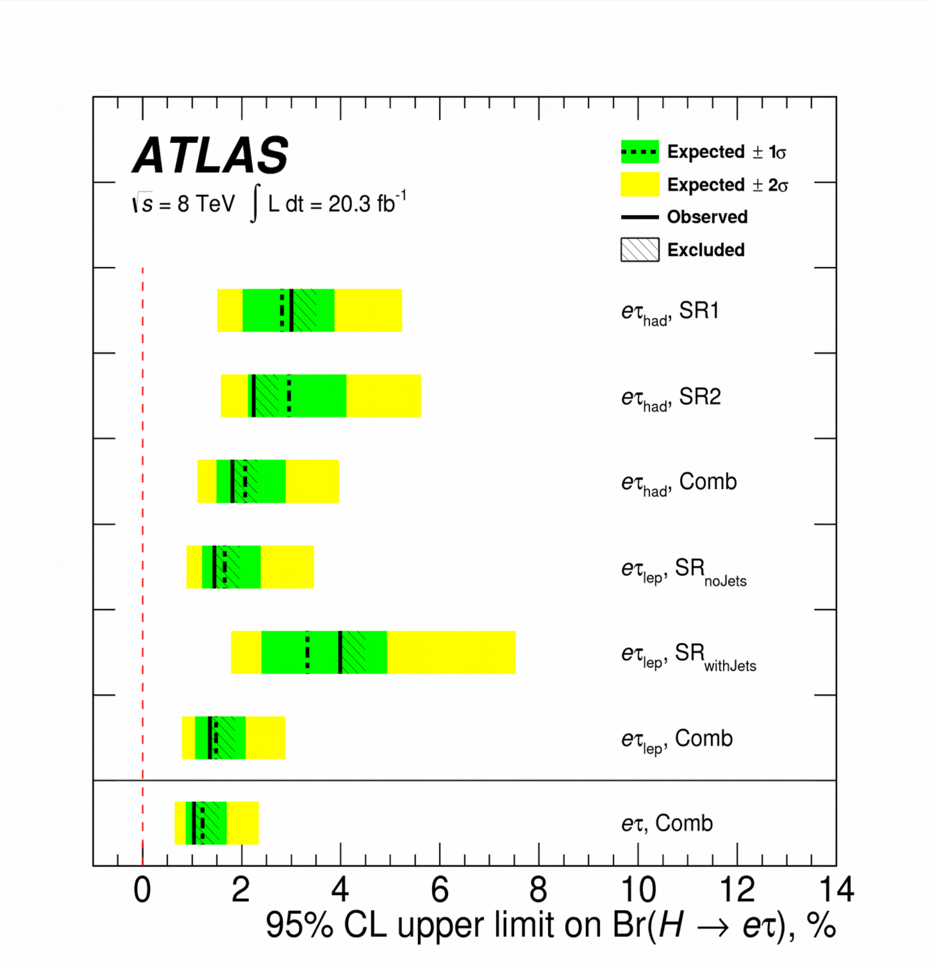


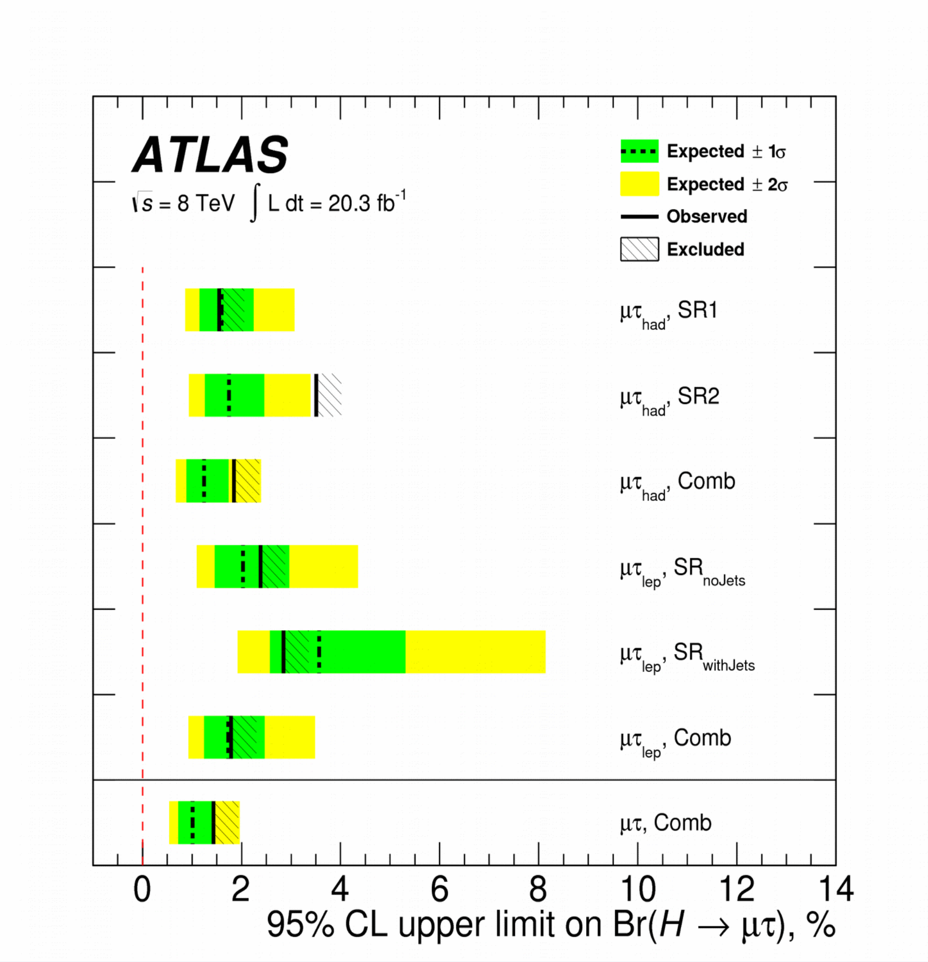
- Combined statistical model to determine scale factor for: symmetric component "non-prompt" contribution signal strength

LFV in Higgs boson decays

arXiv:1604.07730

Combined Results





LFV decays of the Z boson

arXiv:1604.07730
arXiv:1804.09568
arXiv:1408.5774

$Z \to e\mu$, $Z \to \tau e$, $Z \to \tau\mu$

- A $\sqrt{s}$ = 8 TeV $Z \to \tau^{had}\mu$ analysis has been performed with same strategy as $H \to \tau^{had}\mu$
  Br($Z \to \tau\mu$) 1.7 x 10^{-5} (2.6x 10^{-5} expected) [arXiv:1604.07730]
- With 36.1 fb^{-1} of $\sqrt{s}$ = 13 TeV data (2015-2016):
  search $Z \to \tau^{had}e$, $Z \to \tau^{had}\mu$ employing Neural Network [arXiv:1804.09568]
- Dedicated $Z \to e\mu$ analysis with $\sqrt{s}$ = 8 TeV data [arXiv:1408.5774]

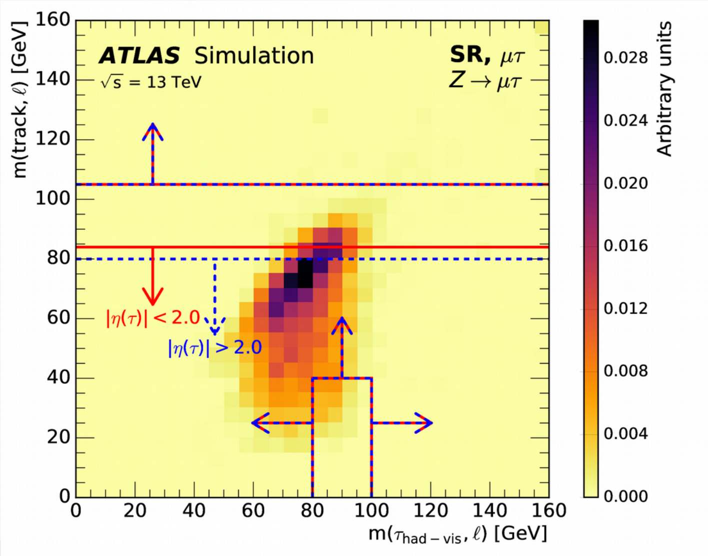
LFV decays of the Z boson: $l\tau$ (hadronic)

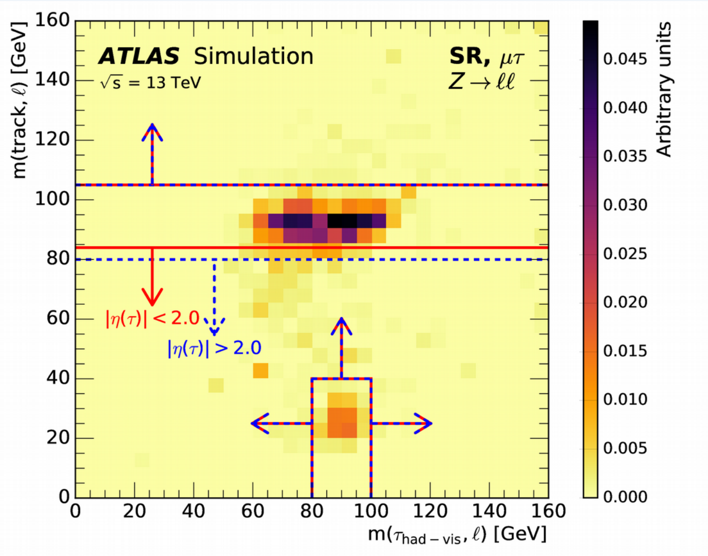
arXiv:1804.09568

$Z \to \tau^{had} e$, $Z \to \tau^{had} \mu$

- Signal Regions distinguish 1-prong from 3-prong τ candidates (# of prompt charged tracks)

- Selection reduce Z→ee/μμ by:
  - Excluding overlapping particles (favouring in this order μ, e, τ)
  - Avoiding regions with higher e→τ and μ→τ misidentification
  - If 1-prong τ, Z mass window for M(τ^{had}, e/μ) and M(track, e/μ)





LFV decays of the Z boson: l τ (hadronic)

arXiv:1804.09568

Neural Network

- Boost into frame in which $\mathbf{E}_T^{miss}+\mathbf{P}_{e/\mu}+\mathbf{P}_{\tau\text{-}vis} = 0$
  and rotation to reduce momenta to 6 parameters (from 12)
- Kinematic discriminant (~0 if $\mathbf{P}_\tau = \alpha\mathbf{P}_{\tau\text{-}vis}$):

$$\Delta\alpha = \frac{1}{2}\frac{m_Z^2 - m_\tau^2}{p(\tau_{\text{had-vis}})\cdot p(\ell)} - \frac{p_T(\ell)}{p_T(\tau_{\text{had-vis}})},$$

Variable	Description	Z NN	Zll NN	W NN
$\hat{E}^{\text{lep}}$	light-lepton energy	✓	✓	✓
$\hat{p}_x^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_x	✓	✓	✓
$\hat{p}_z^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_z	✓	✓	✓
$\hat{E}^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ energy	✓	✓	✓
$\hat{p}_z^{\text{miss}}$	E_T^{miss} component along z-axis	✓	✓	✓
$\hat{E}^{\text{miss}}$	magnitude of E_T^{miss}	✓	✓	✓
p_T^{tot}	transverse component of total momentum	✓	✓	✓
m_{coll}	collinear mass	✓	✓	✓
$\Delta\alpha$		✓	✓	✓
$m(\ell,\tau_{\text{had-vis}})$	invariant mass of light lepton and $\tau_{\text{had-vis}}$		✓	

LFV decays of the Z boson: l τ (hadronic)

arXiv:1804.09568

Evaluation

- Shape of BKG of jets faking τ is determided in data-driven way (*fakes estimate -see backup-*)
- Other backgrounds from validated simulation
- Z decays and fakes are normalized in final fit
- Final discriminants are defined combinin the various Neural Network responses:

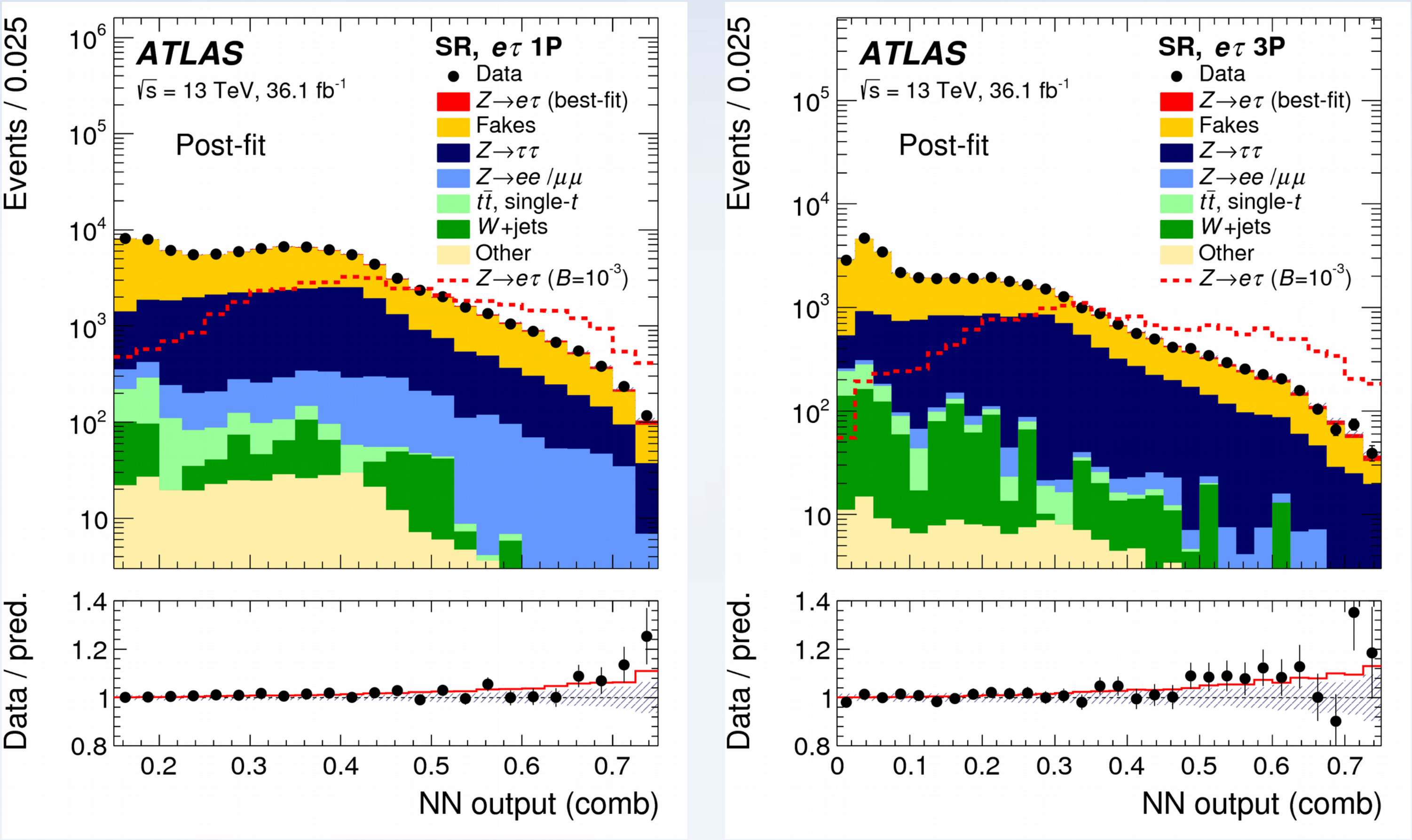
$$\text{combined output(1P)} = 1 - \sqrt{(1-\text{output}_\text{W})^2 + (1-\text{output}_\text{Z})^2 + (1-\text{output}_{\text{Zll}})^2}/\sqrt{3}.$$

$$\text{combined output(3P)} = 1 - \sqrt{(1-\text{output}_\text{W})^2 + (1-\text{output}_\text{Z})^2}/\sqrt{2}.$$

- Binned max-likelihood fit is employed for the following:

	$e\tau$	$\mu\tau$
$\mathcal{B}(Z \to \ell\tau)$	$(3.3^{+1.5}_{-1.4}) \times 10^{-5}$	$(-0.1^{+1.2}_{-1.2}) \times 10^{-5}$
$\mu(Z)$	$0.83^{+0.09}_{-0.07}$	$0.87^{+0.09}_{-0.08}$
μ(fakes_1P)	$1.18^{+0.06}_{-0.06}$	$1.12^{+0.09}_{-0.08}$
μ(fakes_3P)	$1.01^{+0.06}_{-0.05}$	$1.09^{+0.13}_{-0.14}$
Observed (expected) upper limit at 95% CL	$5.8(2.8) \times 10^{-5}$	$2.4(2.4) \times 10^{-5}$

LFV decays of the Z boson: lτ (hadronic)



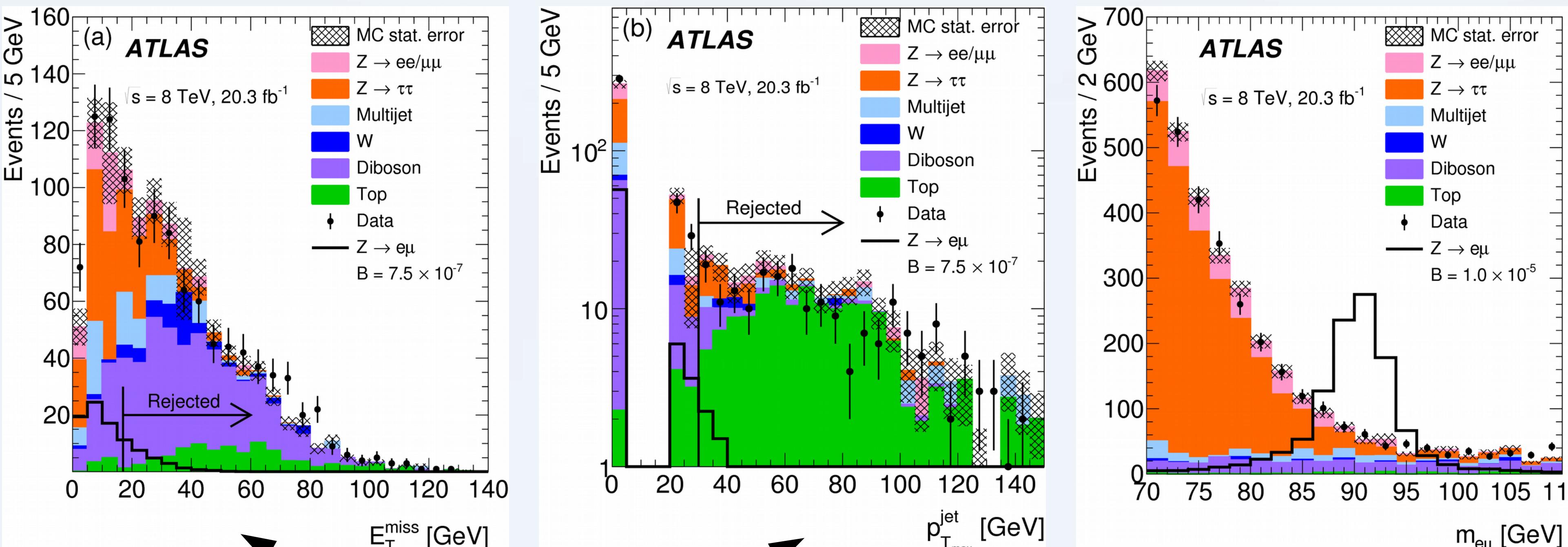
arXiv:1804.09568

- **Limit at Confidence Interval of 95%**
- Br(Z→τe) = 5.8 x 10^{-5} (2.8 x 10^{-5} expected)
  Br(Z→τμ) = 2.4 x 10^{-5} (2.4 x 10^{-5} expected)
  1.3 x 10^{-5} $\sqrt{s}$= 8 & 13 TeV **combined**

LFV decays of the Z boson: Z→eμ

arXiv:1408.5774

- ***Z→eμ search with 20.3 fb^{-1}*** **at $\sqrt{s}$ = 8 TeV**
- Selection of a purified sample of signal-like events:
  - An opposite sign eμ pair in the event
  - Reject high-P_T hadronic activity ($t\bar{t}$)
  - Reject events with considerable E_T^{miss} (WW and Z→ττ)

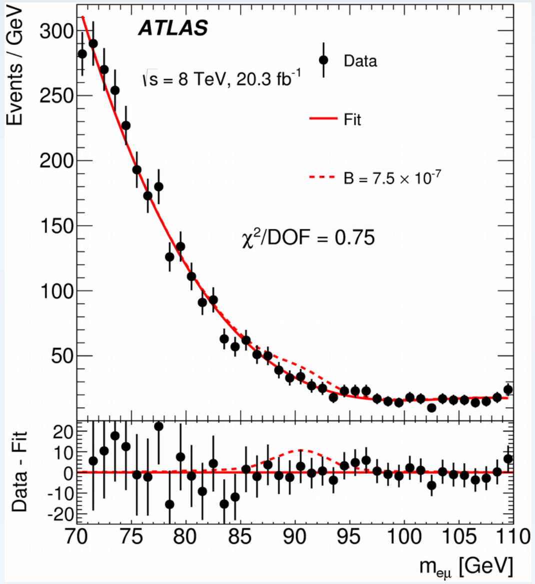


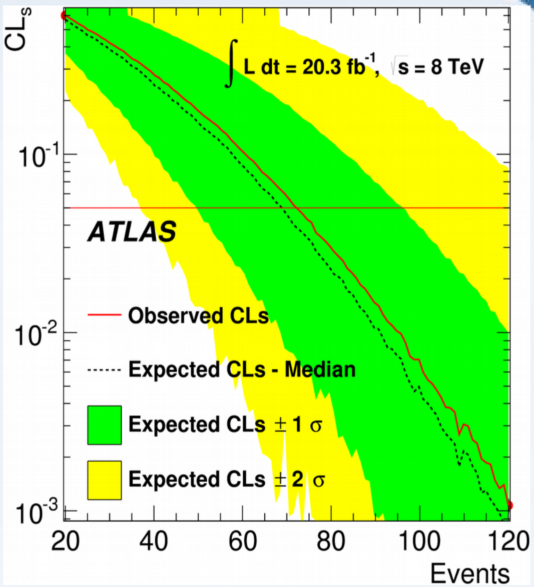
85 GeV < M(e,μ) < 95 GeV

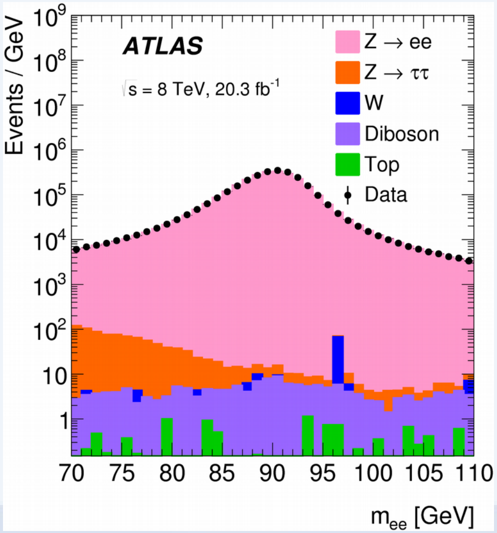
LFV decays of the Z boson: Z→eμ

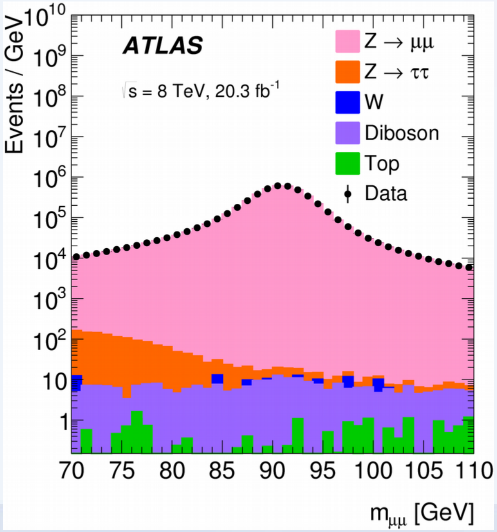
arXiv:1408.5774

- 3rd order Chebychev ploynomial to fit background
- $$Br(Z \to e\mu) = \frac{N_{95\%}}{\epsilon_{e\mu} N_Z}$$
- Number of Z from di-lepton resonance in same range (70 GeV< M_{ll} < 110 GeV)
- Systematics are thus reduced
- Br($Z \to e\mu$) < 7.5 x 10^{-5} (95% CL)









High-mass di-lepton search

arXiv:1607.08079
...

Z' / $\tilde{\nu}_\tau$ / QBH → eμ / eτ / μτ

- Upcoming publication with 36.1 fb^{-1} at $\sqrt{s}$ = 13 TeV (approved preliminary plots)
- Published 3.2 fb^{-1} analysis at $\sqrt{s}$ = 13 TeV (2015)
- Sensitive to di-lepton excesses with M(l,l') > 600 GeV

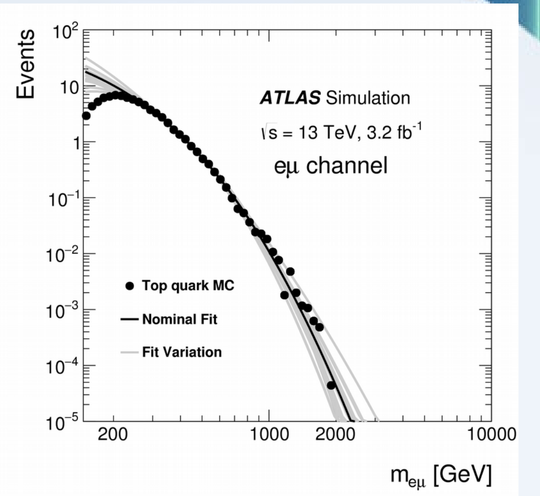
- **Interpretations**:
- Z' with single LFV coupling (each in turn)
- Tau sneutrino in R-parity violating SUSY model
  R-parity violating models can avoid proton decay decoupling violation of B and L
- Quantum Black Holes
  just above threshold energy can lead to few-particle final states violating global symmetries (such as LFC)

R-parity
$P_R = (-1)^{3B+L+2s}$

B = Baryon Number
L = Lepton Number
s = spin

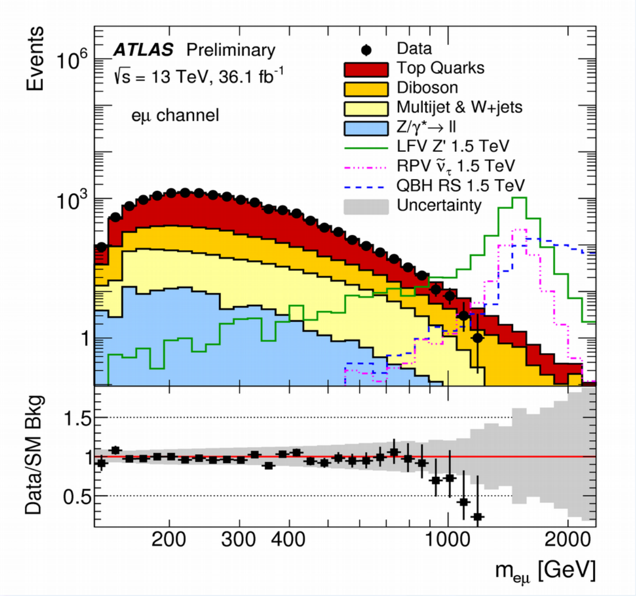
High-mass di-lepton search

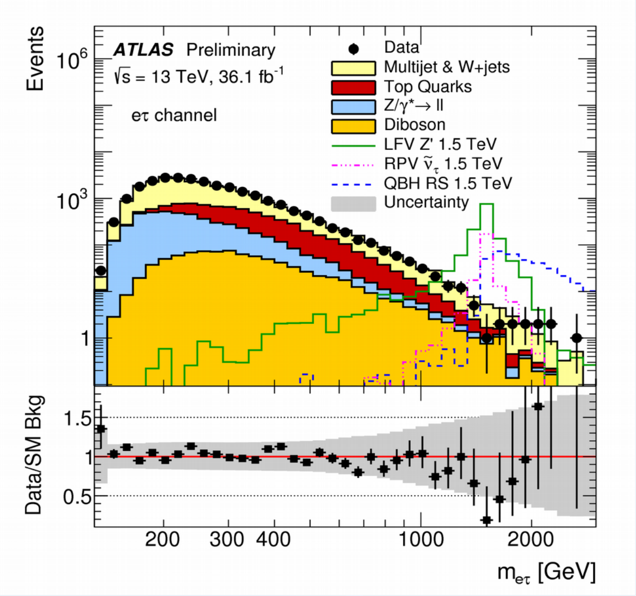
arXiv:1607.08079

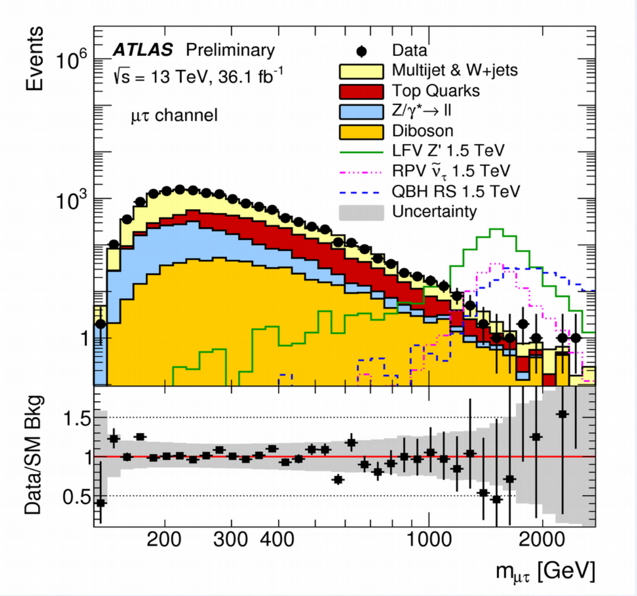


Z’ / $\tilde{\nu}_\tau$ / QBH → eμ / eτ / μτ

- In eμ region fakes are extrapolated from fake-dominated regions
- W+jet is simulation, scaled to match control region
  It is dominating background for eτ and μτ channel
- Single-t and tt taken from simulation, use fit for higher masses
- Other backgrounds are Drell-Yan (Z/γ*→ττ) and di-boson (MC)

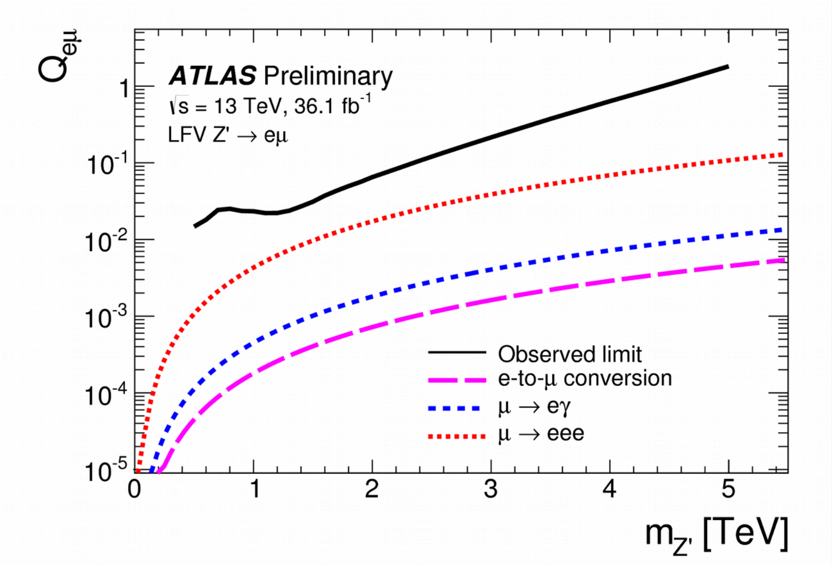


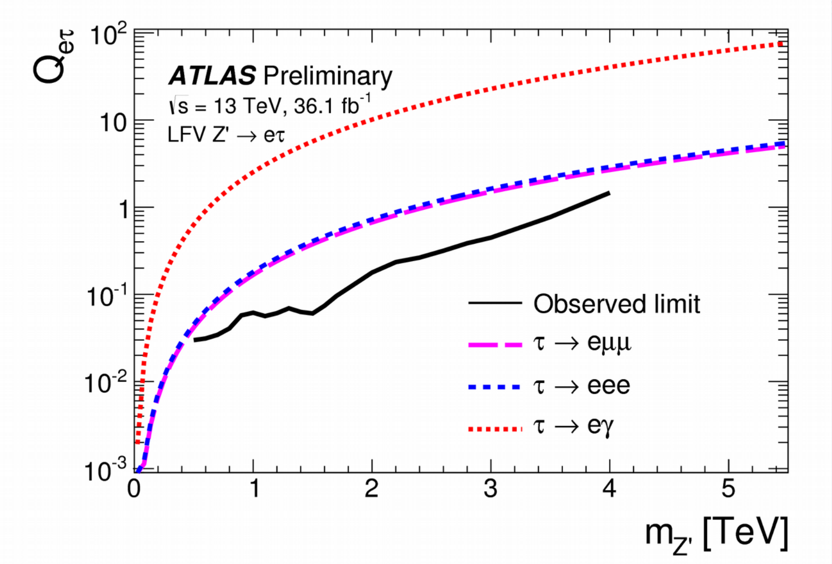


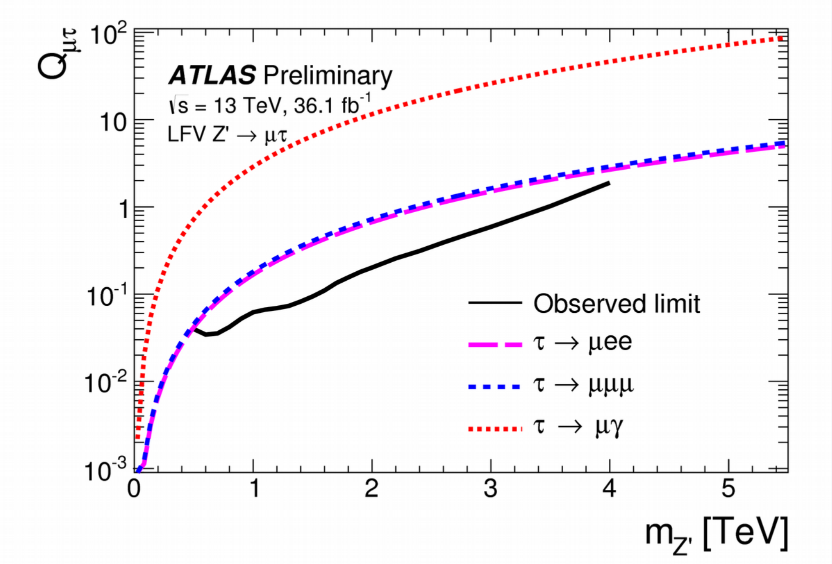


High-mass di-lepton search

Comparison with indirect observation







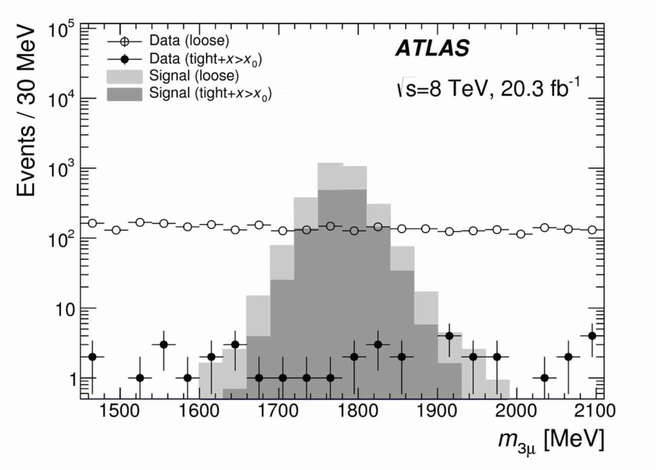
Neutrinoless τ→3μ

arXiv:1601.03567

Neutrinoless τ→ 3μ

- LFV τ decays are the least constrained (amongst charged lepton decays)
- Br(τ→ 3μ) ~10^{-14} in SM, while BSM scenarios predict up to 10^{-8}-10^{-10}

- Searching τ→3μ at a hadron collider is difficult
  low-energy muons have lower reconstruction efficiency
- Need multi-object triggers to select
- Uses W→τν→3μν channel to select on τ boost and E_T^{miss}
- Motivated by multiples of hundreds of millions of τ produced



- Based on 20.3 fb^{-1} of $\sqrt{s}$ = 8 TeV data
- Concept: extrapolation of backgrounds from side-bands into
  |M(3μ) – Mτ| < 1 GeV signal region

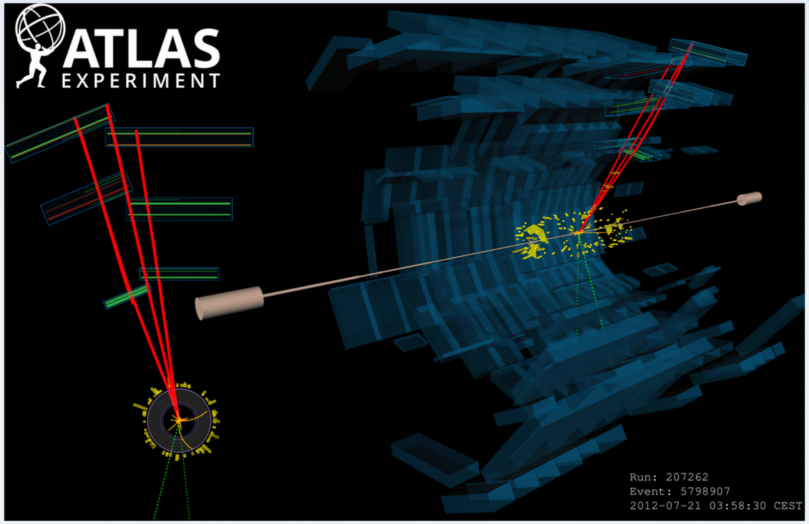
Neutrinoless $\tau \to 3\mu$

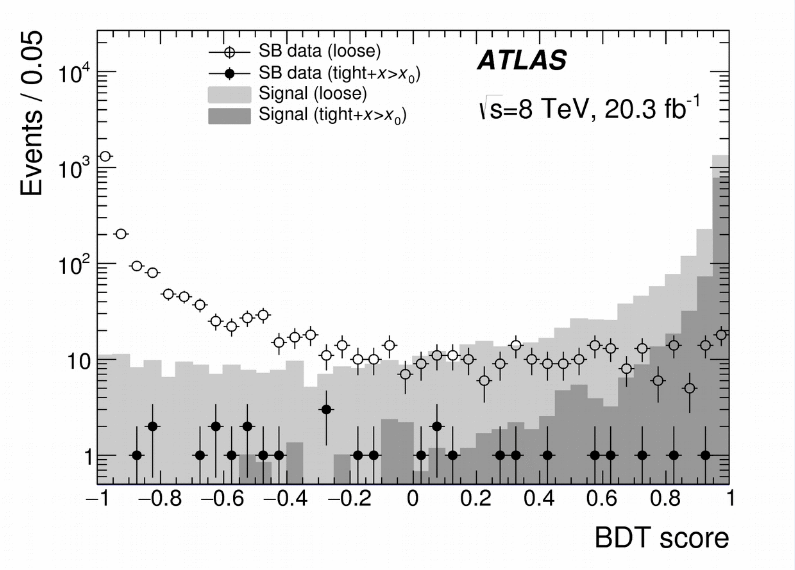
arXiv:1601.03567

$W \to \tau\nu \to 3\mu\nu$

- Basic selection on compact 3μ system and loose E_T^{miss}
- Training of multivariate classifier based on boosted decision trees
- Inputs: angular separations, quality of 3μ vertex, $M_T(3\mu, E_T^{miss})$ and related
- Use of classifier on side-bands after tight selection (OS $\mu\mu$ resonance rejection)

Region	Range in $m_{3\mu}$ [MeV]
Signal region	[1713, 1841]
Blinded region	[1690, 1870]
Sideband region	[1450, 1690] and [1870, 2110]
Training region	[750, 1450] and [2110, 2500]





Neutrinoless $\tau\rightarrow 3\mu$

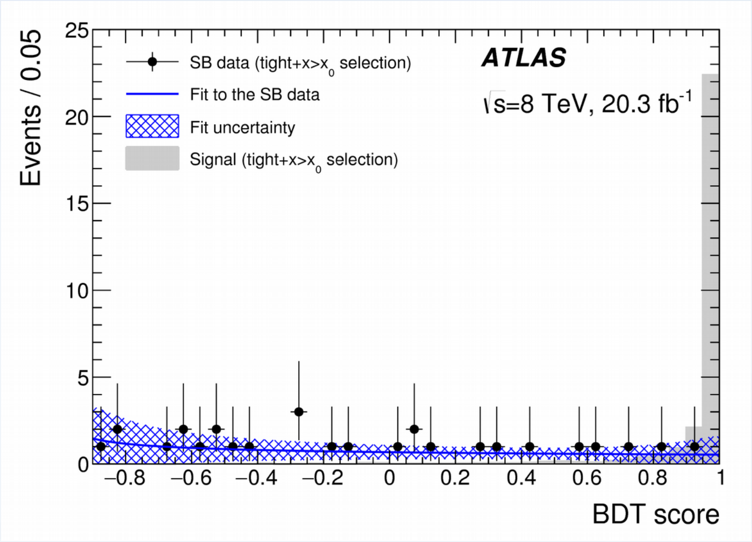
arXiv:1601.03567

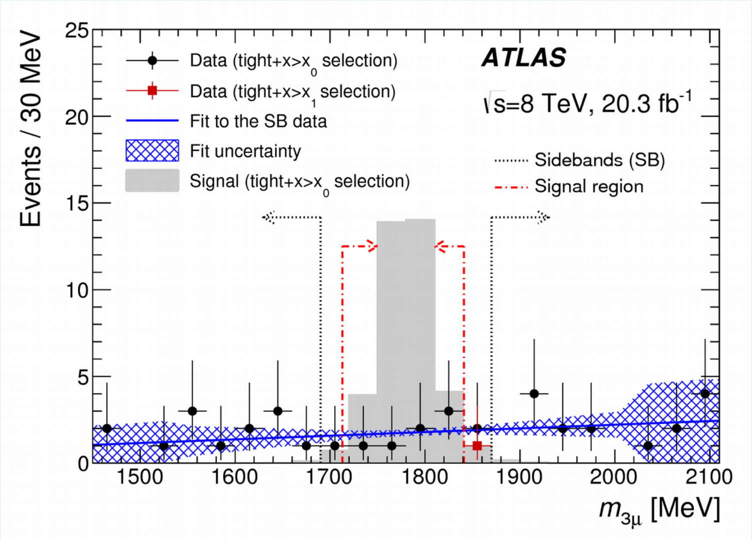
$W\rightarrow\tau\nu\rightarrow 3\mu\nu$

- Classifier cut determined by optimisation of expected limit

- Unblinding found single event outside signal region
- Limit at 90% CL is $Br(\tau\rightarrow 3\mu) < 3.76\times10^{-7}$

- Not yet competitive with LHCb or b-factories
- Search proved ATLAS potential for search
- Expected to be competitive with Belle at the end of Run2 (dataset including 2018)





Summary

- Showed results of searches for LFV in:
  - $H \to ll'$ (arXiv:1508.03372 , arXiv:1604.07730)
  - $Z \to ll'$ (arXiv:1408.5774, arXiv:1604.07730, arXiv:1804.09568)
  - $X \to ll'$ (arXiv:1607.08079, ...)
  - $\tau \to 3\mu$ (arXiv:1601.03567)

- Some channels are limited to $\sqrt{s}$ = 8 TeV data
- Searches are still in progress
- Run2 will yield > 100 fb^{-1} of data (2015-2018)

- Stay tuned for updates!

Backup

LFV in Higgs boson decays: hadronic-τ

arXiv:1604.07730

- Regions for $H\rightarrow\tau^{had}\mu$ are identical up to use of $P_T(\mu)$ replacing $E_T(e)$

Criterion	SR1	SR2	WCR	TCR
$E_T(e)$	>26 GeV	>26 GeV	>26 GeV	>26 GeV
$p_T(\tau_{had})$	>45 GeV	>45 GeV	>45 GeV	>45 GeV
$\|\eta(e) - \eta(\tau_{had})\|$	<2	<2	<2	<2
$m_T^{e,E_T^{miss}}$	>40 GeV	<40 GeV	>60 GeV	–
$m_T^{\tau_{had},E_T^{miss}}$	<30 GeV	<60 GeV	>40 GeV	–
N_{jet}	–	–	–	≥2
N_{b-jet}	0	0	0	≥1

LFV in Higgs boson decays: hadronic-τ

arXiv:1604.07730

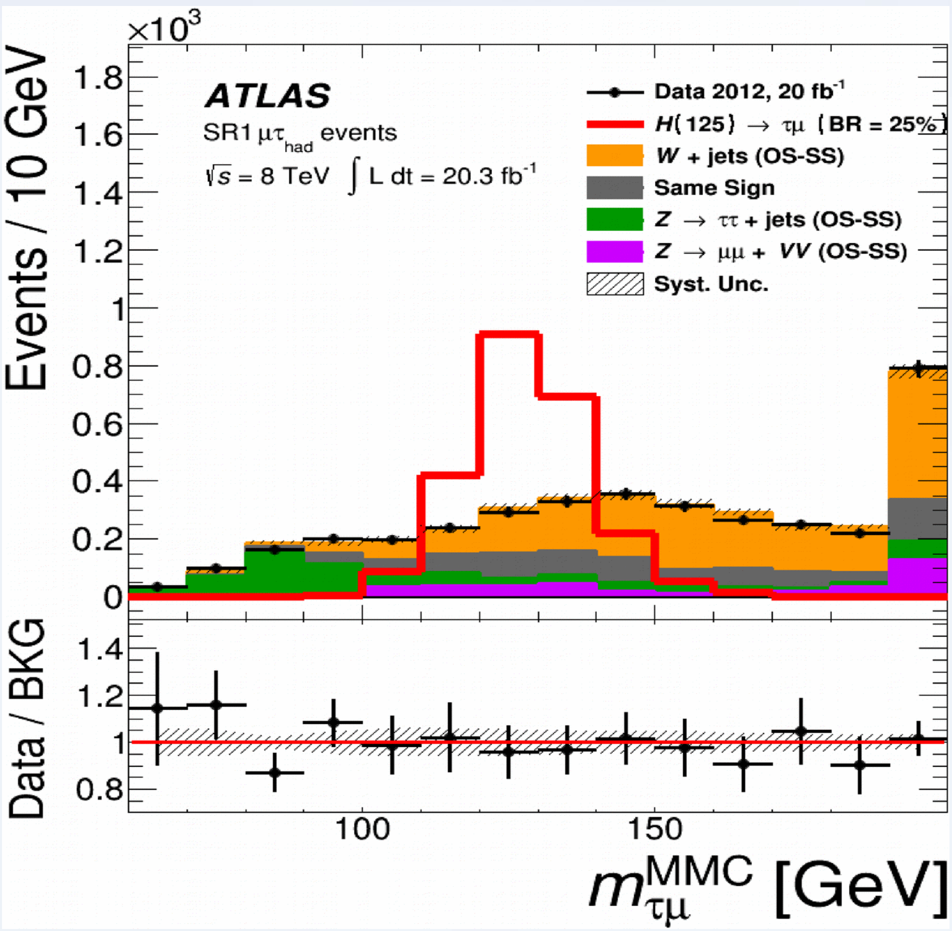
- Signal Region yields

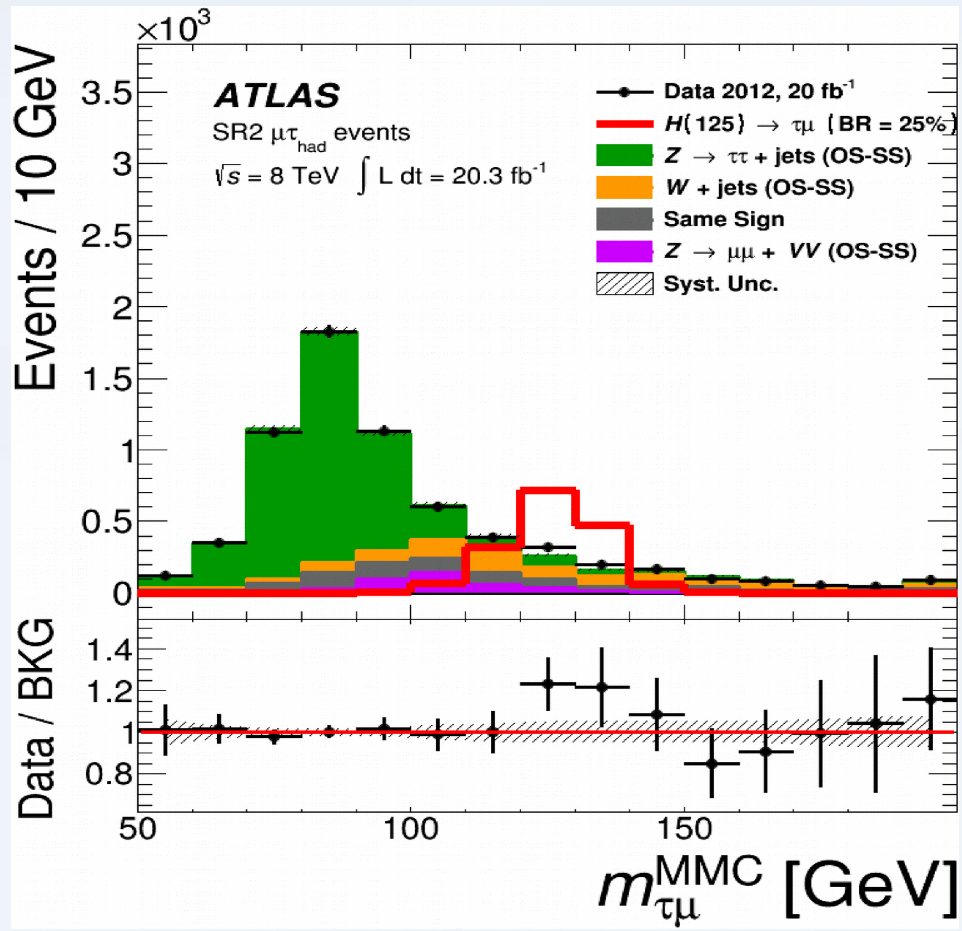
	SR1			SR2		
LFV signal ($\mathrm{Br}(H \to e\tau) = 1.0\%$)	75	± 1	± 8	59	± 1	± 8
W+jets	740	±80	±110	370	±60	±70
Same-Sign events	390	±20	± 60	570	±30	±80
$Z \to \tau\tau$	116	± 8	± 11	245	±11	±20
$VV + Z \to ee(jet \to \tau_{\mathrm{had}}^{\mathrm{misid}})$	71	±31	± 30	60	±20	±40
$Z \to ee(e \to \tau_{\mathrm{had}}^{\mathrm{misid}})$	69	±17	± 11	320	±40	±40
Top	18	± 5	± 4	10.2	± 2.6	± 2.2
$H \to \tau\tau$	4.6	± 0.2	± 0.7	10.5	± 0.3	± 1.5
Total background	1410	±90	± 70	1590	±80	±70
Data	1397			1501		

LFV in Higgs boson decays: hadronic-τ

arXiv:1508.03372
arXiv:1604.07730

- Discriminant distribution for τμ





LFV in Higgs boson decays: leptonic-τ

arXiv:1604.07730

- Signal Regions

	SR_{noJets}	$SR_{withJets}$
Light leptons	$e^{\pm}\mu^{\mp}$	$e^{\pm}\mu^{\mp}$
τ leptons	veto	veto
Central jets	0	≥ 1
b-jets	0	0
$p_T^{\ell_1}$	$\geq 35GeV$	$\geq 35GeV$
$p_T^{\ell_2}$	$\geq 12GeV$	$\geq 12GeV$
$\lvert\eta^e\rvert$	≤ 2.4	≤ 2.4
$\lvert\eta^\mu\rvert$	≤ 2.4	≤ 2.4
$\Delta\phi(\ell_2, E_T^{miss})$	≤ 0.7	≤ 0.5
$\Delta\phi(\ell_1, \ell_2)$	≥ 2.3	≥ 1.0
$\Delta\phi(\ell_1, E_T^{miss})$	≥ 2.5	≥ 1.0
$\Delta p_T(\ell_1, \ell_2)$	$\geq 7GeV$	$\geq 1GeV$

LFV in Higgs boson decays: leptonic-τ

arXiv:1604.07730

- Efficiency correction factors for $P_T(l_2)$ and yields in Signal Region

SR_{noJets}					
$p_T^{\ell_2}$ bin [GeV]	$f\left(p_T^{\ell_2}\right)$		LFV Signal, Br=1%	Total Backg.	Observed
12–20	1.11 ± 0.06	$e\mu$	$14.9 \pm 0.4 \pm 2.7$	$1219 \pm 24 \pm 27$	1212
		μe	$10.7 \pm 0.4 \pm 2.3$	$1033 \pm 25 \pm 20$	1035
20–30	1.07 ± 0.08	$e\mu$	$15.1 \pm 0.4 \pm 2.7$	$998 \pm 22 \pm 25$	995
		μe	$12.4 \pm 0.4 \pm 2.2$	$950 \pm 23 \pm 21$	950
≥ 30	1.01 ± 0.07	$e\mu$	$12.5 \pm 0.4 \pm 2.2$	$455 \pm 17 \pm 16$	452
		μe	$11.4 \pm 0.4 \pm 2.0$	$458 \pm 16 \pm 14$	457
$SR_{withJets}$					
$p_T^{\ell_2}$ bin [GeV]	$f\left(p_T^{\ell_2}\right)$		LFV Signal, Br=1%	Total Backg.	Observed
12–20	1.07 ± 0.10	$e\mu$	$5.9 \pm 0.3 \pm 1.1$	$222 \pm 10 \pm 11$	220
		μe	$3.9 \pm 0.2 \pm 0.9$	$181 \pm 10 \pm 9$	182
20–30	1.24 ± 0.16	$e\mu$	$5.4 \pm 0.2 \pm 1.1$	$187 \pm 9 \pm 11$	187
		μe	$4.5 \pm 0.2 \pm 0.9$	$161 \pm 9 \pm 9$	161
≥ 30	1.13 ± 0.10	$e\mu$	$5.5 \pm 0.2 \pm 1.0$	$251 \pm 11 \pm 12$	250
		μe	$4.9 \pm 0.2 \pm 0.9$	$229 \pm 11 \pm 11$	229

LFV in Higgs boson decays: all

arXiv:1604.07730

- Result Summary with combination

Channel	Category	Expected limit [%]	Observed limit [%]	Best fit Br [%]
$H \to e\tau_{\text{had}}$	SR1	$2.81^{+1.06}_{-0.79}$	3.0	$0.33^{+1.48}_{-1.59}$
	SR2	$2.95^{+1.16}_{-0.82}$	2.24	$-1.33^{+1.56}_{-1.80}$
	Combined	$2.07^{+0.82}_{-0.58}$	1.81	$-0.47^{+1.08}_{-1.18}$
$H \to e\tau_{\text{lep}}$	$\text{SR}_{\text{noJets}}$	$1.66^{+0.72}_{-0.46}$	1.45	$-0.45^{+0.89}_{-0.97}$
	$\text{SR}_{\text{withJets}}$	$3.33^{+1.60}_{-0.93}$	3.99	$0.74^{+1.59}_{-1.62}$
	Combined	$1.48^{+0.60}_{-0.42}$	1.36	$-0.26^{+0.79}_{-0.82}$
$H \to e\tau$	Combined	$1.21^{+0.49}_{-0.34}$	1.04	$-0.34^{+0.64}_{-0.66}$
$H \to \mu\tau_{\text{had}}$	SR1	$1.60^{+0.64}_{-0.45}$	1.55	$-0.07^{+0.81}_{-0.86}$
	SR2	$1.75^{+0.71}_{-0.49}$	3.51	$1.94^{+0.92}_{-0.89}$
	Combined	$1.24^{+0.50}_{-0.35}$	1.85	$0.77^{+0.62}_{-0.62}$
$H \to \mu\tau_{\text{lep}}$	$\text{SR}_{\text{noJets}}$	$2.03^{+0.93}_{-0.57}$	2.38	$0.31^{+1.06}_{-0.99}$
	$\text{SR}_{\text{withJets}}$	$3.57^{+1.74}_{-1.00}$	2.85	$-1.03^{+1.66}_{-1.82}$
	Combined	$1.73^{+0.74}_{-0.49}$	1.79	$0.03^{+0.88}_{-0.86}$
$H \to \mu\tau$	Combined	$1.01^{+0.40}_{-0.29}$	1.43	$0.53^{+0.51}_{-0.51}$

LFV decays of the Z boson: μ τ (hadronic)

arXiv:1604.07730

- Signal Regions (H-like analysis)
  Note differences w.r.t. H selections

Cut	SR1	SR2	WCR	TCR
$p_{\mathrm{T}}(\mu)$	>30 GeV	>30 GeV	>30 GeV	>30 GeV
$p_{\mathrm{T}}(\tau_{\mathrm{had}})$	>30 GeV	>30 GeV	>30 GeV	>30 GeV
$\lvert\eta(\mu) - \eta(\tau_{\mathrm{had}})\rvert$	<2	<2	<2	<2
$m_{\mathrm{T}}^{\mu, E_{\mathrm{T}}^{\mathrm{miss}}}$	>30 GeV and <75 GeV	<30 GeV	>60 GeV	–
$m_{\mathrm{T}}^{\tau_{\mathrm{had}}, E_{\mathrm{T}}^{\mathrm{miss}}}$	<20 GeV	<45 GeV	>40 GeV	–
N_{jet}	–	–	–	>1
$N_{b-\mathrm{jet}}$	0	0	0	>0

LFV decays of the Z boson: $\mu\tau$ (hadronic)

arXiv:1604.07730

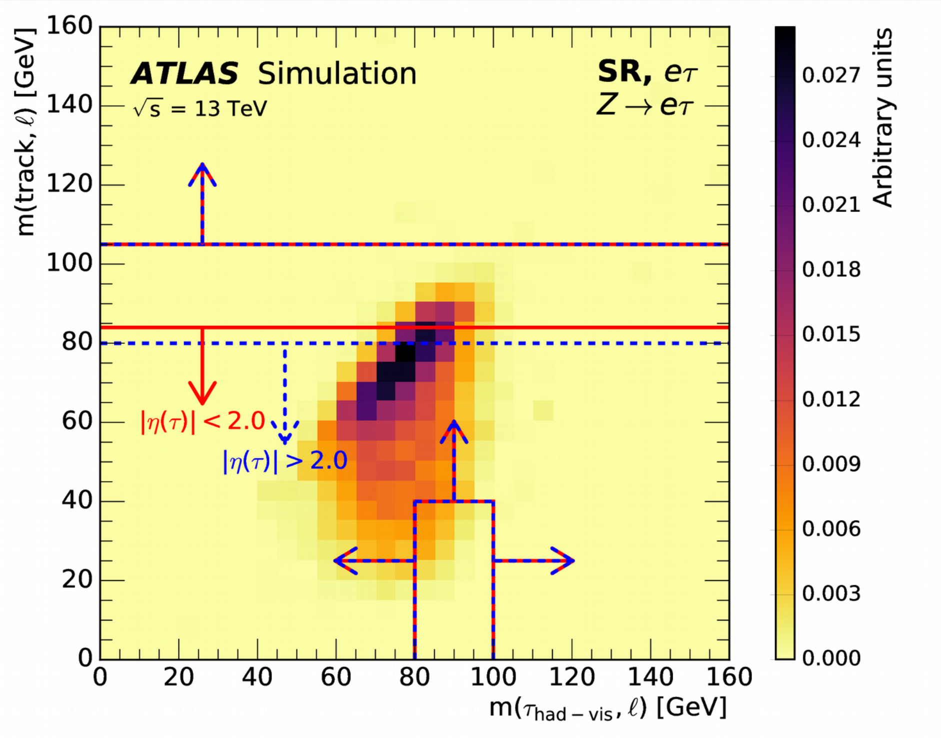
- Signal Region yields (H-like analysis)

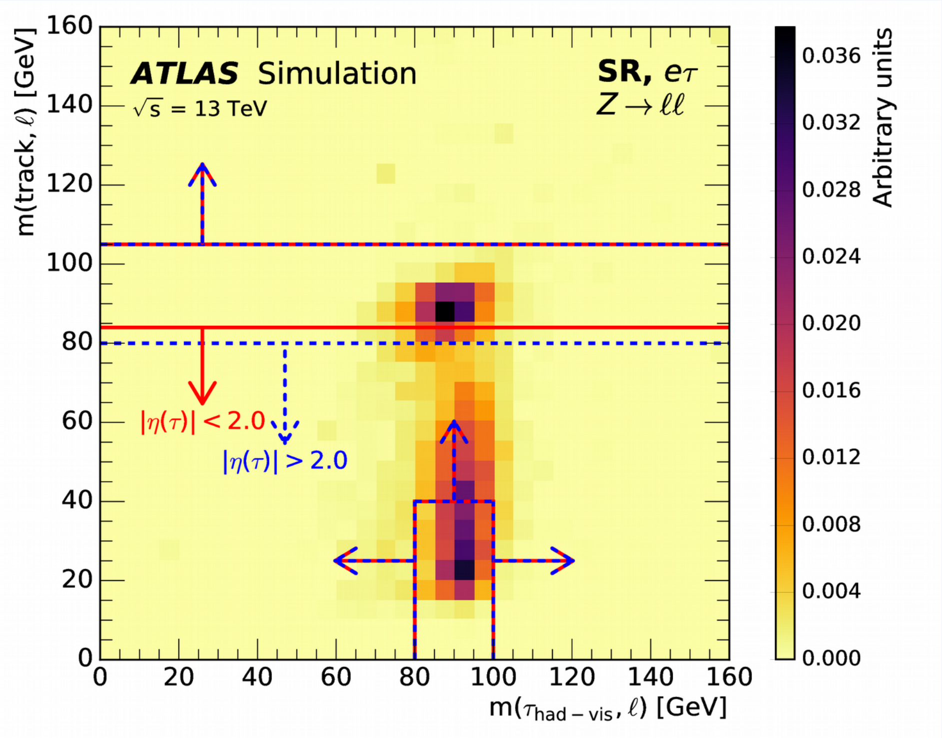
	SR1	SR2
Signal	$86 \pm 2 \pm 22$	$56 \pm 2 \pm 18$
$Z \to \tau\tau$	$3260 \pm 30 \pm 60$	$7060 \pm 40 \pm 150$
W+jets	$1350 \pm 70 \pm 110$	$590 \pm 50 \pm 70$
Same–Sign events	$1110 \pm 40 \pm 100$	$930 \pm 30 \pm 90$
$VV + Z \to \mu\mu$	$410 \pm 60 \pm 50$	$240 \pm 60 \pm 60$
$H \to \tau\tau$	$25.1 \pm 0.5 \pm 3.0$	$41 \pm 1 \pm 5$
Top	$22 \pm 4 \pm 4$	$15 \pm 4 \pm 4$
Total background	$6170 \pm 100 \pm 100$	$8880 \pm 100 \pm 140$
Data	6134	8982

LFV decays of the Z boson: $l\tau$ (hadronic)

arXiv:1804.09568

- Pre-selection cuts explained for eτ





LFV decays of the Z boson: $l\tau$ (hadronic)

arXiv:1804.09568

- Signal Regions and pre-selections for the analysis

Preselection	one isolated tight light lepton with $p_{\mathrm{T}} > 30$ GeV matched to a lepton selected at trigger level
	leading $\tau_{\text{had-vis}}$ with $p_{\mathrm{T}} > 20$ GeV, $N_{\tau}^{\text{tracks}} = 1$ or 3 and passing tight identification
	if $N_{\tau}^{\text{tracks}} = 1$: $0.0(0.1) < \lvert\eta_{\tau}\rvert < 1.37$ or $1.52 < \lvert\eta_{\tau}\rvert < 2.2(2.5)$ in $e\tau(\mu\tau)$ events
	if $N_{\tau}^{\text{tracks}} = 3$: $0.0 < \lvert\eta_{\tau}\rvert < 1.37$ or $1.52 < \lvert\eta_{\tau}\rvert < 2.5$
	$q_{\ell} \times q_{\tau} = -1$
	no b-jet, no additional light lepton
Signal Region	$m_{\mathrm{T}}(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\text{miss}}) < 35(30)$ GeV in $e\tau$ $(\mu\tau)$ events
	if $N_{\tau}^{\text{tracks}} = 1$ and $\lvert\eta_{\tau}\rvert < 2.0$: $m(\text{track}, \ell) < 84$ GeV or $m(\text{track}, \ell) > 105$ GeV
	if $N_{\tau}^{\text{tracks}} = 1$ and $\lvert\eta_{\tau}\rvert > 2.0$: $m(\text{track}, \ell) < 80$ GeV or $m(\text{track}, \ell) > 105$ GeV
	if $N_{\tau}^{\text{tracks}} = 1$ and $80 < m(\tau_{\text{had-vis}}, \ell) < 100$ GeV: $m(\text{track}, \ell) > 40$ GeV

LFV decays of the Z boson: $l\tau$ (hadronic)

arXiv:1804.09568

- Control Regions

Region	Change relative to SR selection	Purity [%] $e\tau$	Purity [%] $\mu\tau$
CRZll	Two same-flavor opposite-charge light leptons with $81 < m_{\ell\ell} < 101$ GeV	98	98
CRW	$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > 40$ GeV and $m_{\mathrm{T}}(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\mathrm{miss}}) > 35(30)$ GeV in $e\tau$ ($\mu\tau$) events	84	85
CRT	$N_{b\text{-jets}} \geq 2$	98	98
CRQ	Inverted light-lepton isolation	75	37

LFV decays of the Z boson: $l\tau$ (hadronic)

arXiv:1804.09568

Fakes Estimate: **$Z \to \tau^{had} e$, $Z \to \tau^{had} \mu$**

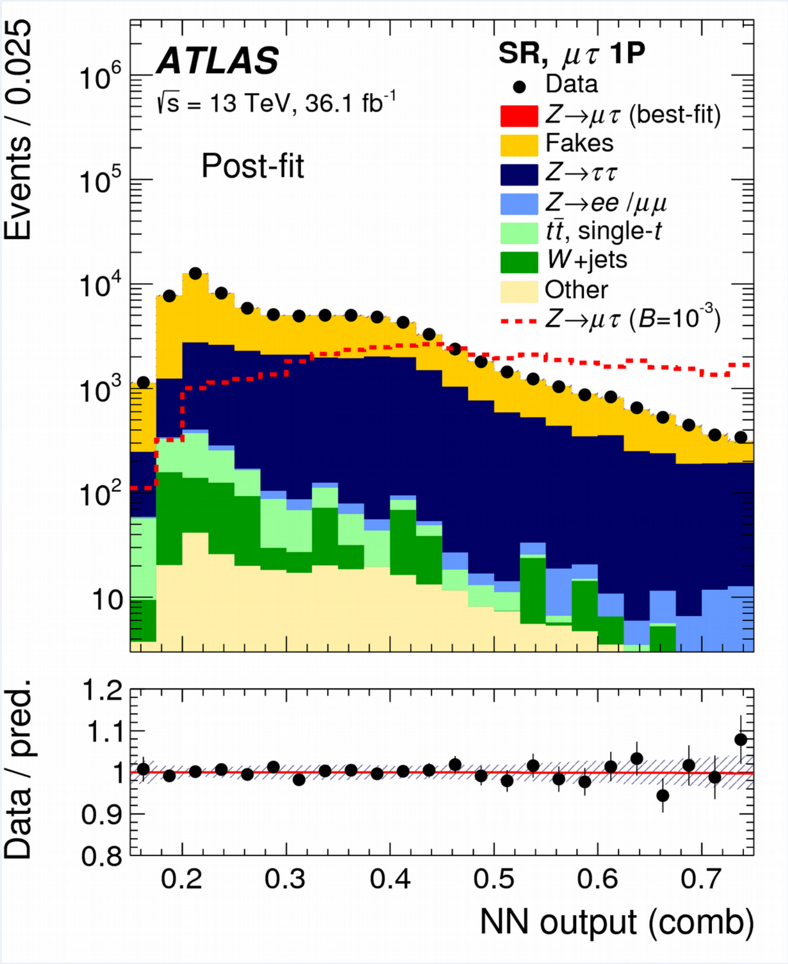
- BKG contribution of jets faking taus are accounted fakes estimate
- Estimate based on "fake sideband" selections using reversed selection cuts
- Counts are transferred into the Signal Region using simulation-based factors

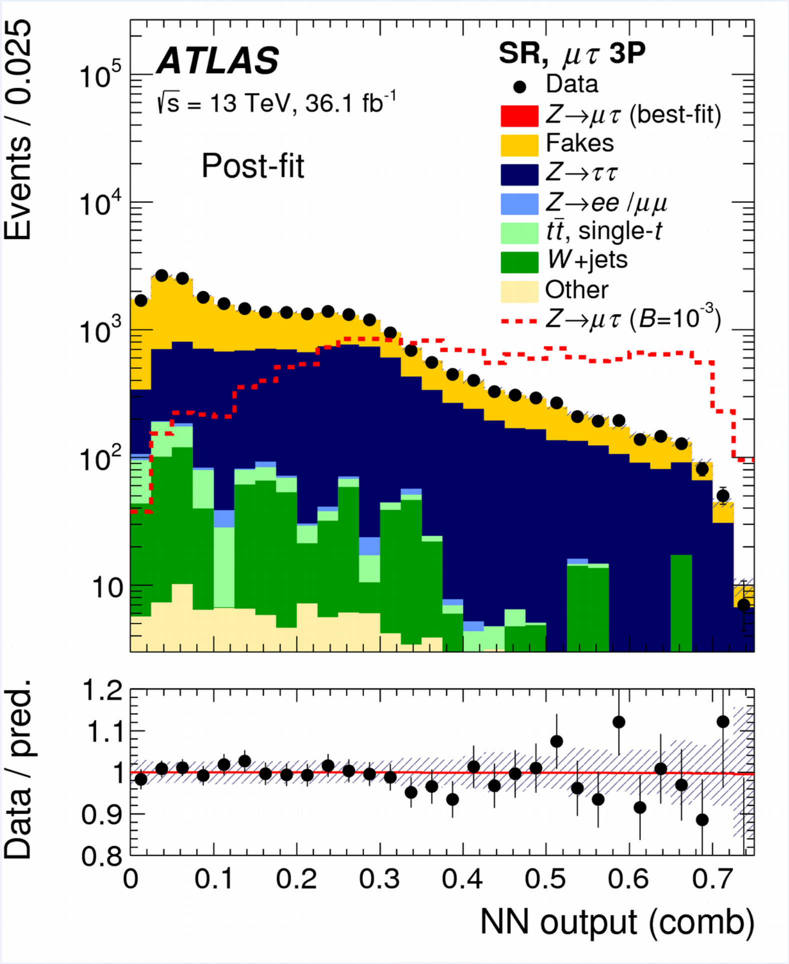
$$N_{\mathrm{SR}}^{\mathrm{fake}} = \sum_k \left(N_{\mathrm{SR,data}}^{\mathrm{fail}} - N_{\mathrm{SR,MC,not\ jet}\to\tau}^{\mathrm{fail}} \right)_k \times F_k,$$

LFV decays of the Z boson: l τ (hadronic)

arXiv:1804.09568

- $Z \rightarrow \tau^{had}\mu$ discriminants post-fit





LFV decays of the Z boson: $l\tau$ (hadronic)

arXiv:1804.09568

	1-prong	3-prong
Total observed $e\tau$ events	89 294	35 148
Total post-fit $e\tau$ events	89 300±300	35 200±200
Fakes	57 000±1000	21 500±500
$Z \to \tau\tau$	26 000±1000	11 500±500
$Z \to \ell\ell$	3200±100	250±150
Top	770±120	440±70
W+jets	540±100	950±180
Other	340±70	150±30
$Z \to \tau e$ signal	900±400	390±160
Total observed $\mu\tau$ events	79 744	25 050
Total post-fit $\mu\tau$ events	79 700±500	25 100±700
Fakes	52 000±1000	13 600±800
$Z \to \tau\tau$	26 000±1000	10 300±300
$Z \to \ell\ell$	240±110	80±40
Top	890±140	360±60
W+jets	610±120	680±130
Other	290±70	110±20
$Z \to \tau\mu$ signal	−20±360	−10±140

High-mass di-lepton search

arXiv:1607.08079

- High-mass yields **eμ**

Process	$m_{e\mu} < 600$ GeV	$m_{e\mu} > 600$ GeV
Top quark	1190 ± 140	22 ± 5
Diboson	159 ± 17	4.9 ± 0.9
Multi-jet and W+jets	55 ± 11	2.7 ± 1.7
$Z/\gamma^* \rightarrow \ell\ell$	14.5 ± 2.0	0.18 ± 0.04
Total SM background	1410 ± 150	30 ± 7
SM+Z' ($M_{Z'} = 2$ TeV)	-	75 ± 13
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau} = 2$ TeV)	-	40 ± 8
SM+QBH RS $n = 1$ ($M_{\mathrm{th}} = 2$ TeV)	-	44 ± 9
Data	1463	25

(a) $e\mu$ channel

High-mass di-lepton search

arXiv:1607.08079

- High-mass yields **$e\tau$**

Process	$m_{e\tau}$ < 600 GeV	$m_{e\tau}$ > 600 GeV
Top quark	790 ± 190	25 ± 9
Diboson	109 ± 26	6.2 ± 1.9
Multi-jet and W+jets	3200 ± 800	45 ± 14
$Z/\gamma^* \to \ell\ell$	1030 ± 240	5.2 ± 1.4
Total SM background	5200 ± 1300	81 ± 25
SM+Z' ($M_{Z'}$ = 1.5 TeV)	-	185 ± 34
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau}$ = 1.5 TeV)	-	105 ± 27
SM+QBH RS $n = 1$ (M_{th} = 1.5 TeV)	-	122 ± 28
Data	5416	111

(b) $e\tau$ channel

High-mass di-lepton search

arXiv:1607.08079

- High-mass yields $\mu\tau$

Process	$m_{\mu\tau} < 600$ GeV	$m_{\mu\tau} > 600$ GeV
Top quark	580 ± 140	21 ± 7
Diboson	84 ± 20	4.8 ± 1.4
Multi-jet and W+jets	1900 ± 500	34 ± 12
$Z/\gamma^* \to \ell\ell$	610 ± 140	2.6 ± 0.7
Total SM background	3200 ± 800	63 ± 20
SM+Z' ($M_{Z'} = 1.5$ TeV)	-	130 ± 28
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau} = 1.5$ TeV)	-	78 ± 22
SM+QBH RS $n = 1$ ($M_{\text{th}} = 1.5$ TeV)	-	90 ± 23
Data	3239	48

(c) $\mu\tau$ channel

High-mass di-lepton search

arXiv:1607.08079

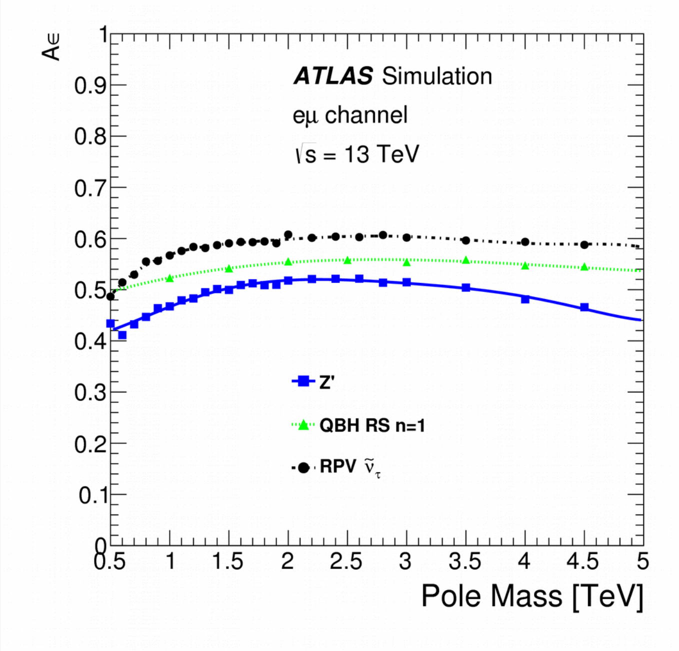
- Uncertainties

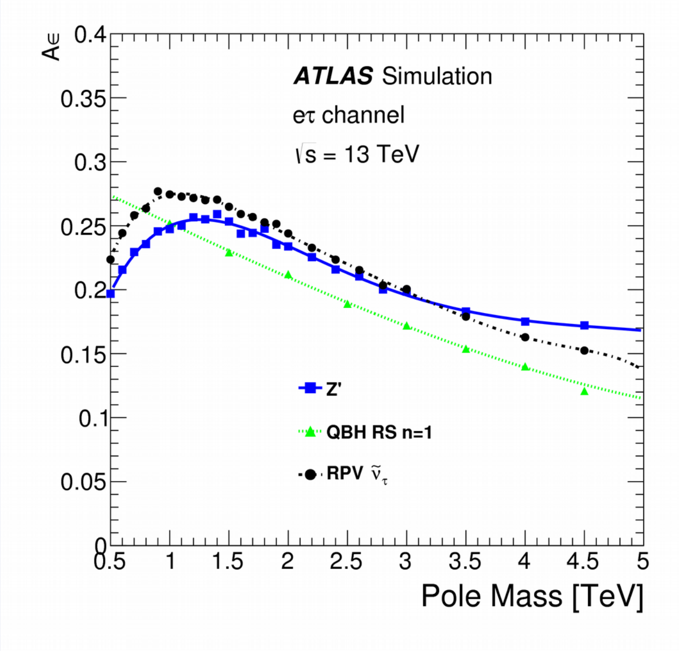
Source	$m_{\ell\ell'}$ = 1 TeV			$m_{\ell\ell'}$ = 2 TeV			$m_{\ell\ell'}$ = 3 TeV		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
PDF uncertainty	17%	15%	15%	35%	38%	35%	70%	75%	70%
Luminosity	5%	5%	5%	5%	5%	5%	5%	5%	5%
Statistical	18%	11%	15%	80%	27%	27%	120%	28%	30%
Reducible background	5%	29%	40%	5%	35%	75%	5%	45%	85%
Top quark production modelling	5%	3%	4%	12%	4%	5%	15%	10%	8%
Electron trigger efficiency	1%	1%	N/A	1%	1%	N/A	1%	1%	N/A
Electron identification	2%	2%	N/A	2%	2%	N/A	2%	2%	N/A
Electron energy scale and resolution	3%	3%	N/A	3%	3%	N/A	3%	3%	N/A
Muon reconstruction efficiency	2%	N/A	2%	4%	N/A	4%	6%	N/A	6%
Muon scale and resolution	4%	N/A	4%	12%	N/A	12%	20%	N/A	20%
Muon trigger efficiency	2%	N/A	2%	2%	N/A	2%	2%	N/A	2%
Tau identification	N/A	4%	4%	N/A	5%	5%	N/A	6%	6%
Tau reconstruction	N/A	3%	3%	N/A	4%	4%	N/A	4%	4%
Tau energy calibrations	N/A	2%	2%	N/A	3%	3%	N/A	4%	4%
Total	27%	35%	44%	90%	59%	90%	140%	90%	120%
SM Background in $m_{\ell\ell'} \pm 0.1 \cdot m_{\ell\ell'}$	3.9	11.9	11.4	0.09	0.55	0.49	0.002	0.014	0.017

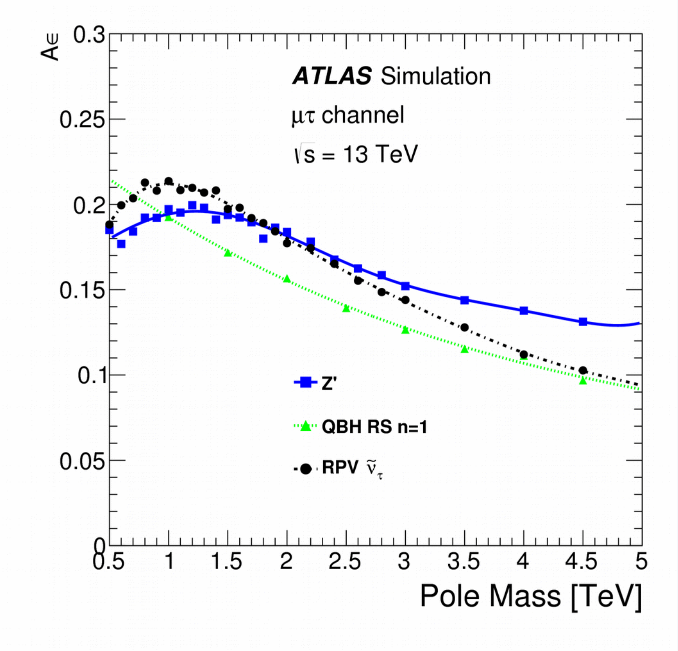
High-mass di-lepton search

arXiv:1607.08079

Acceptance*Efficiency signals







High-mass di-lepton search

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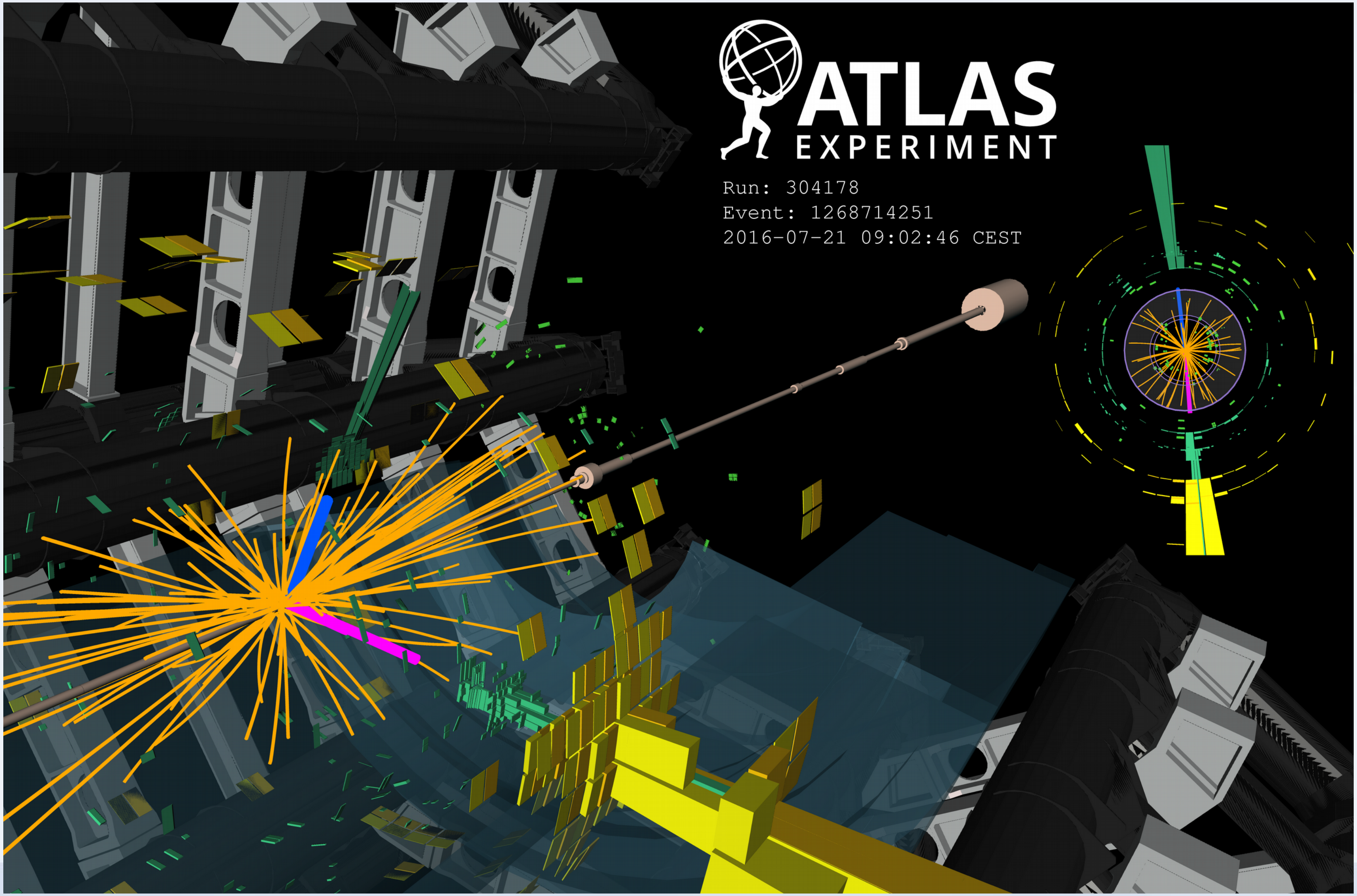
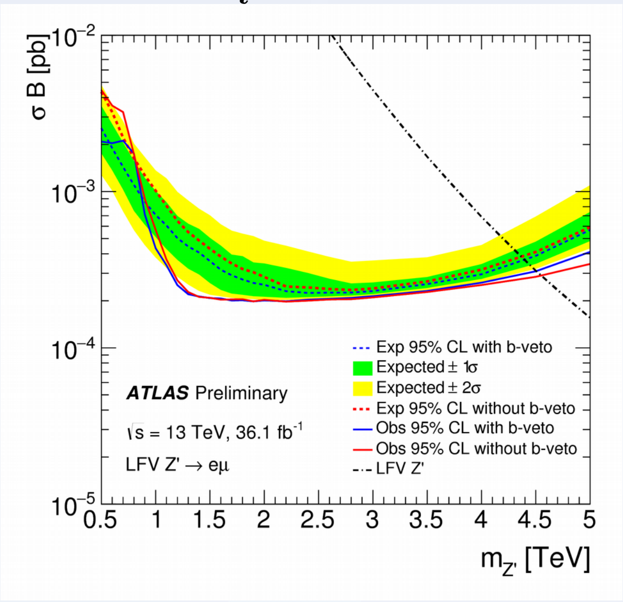
Highest-energy eτ event (2.58 TeV)

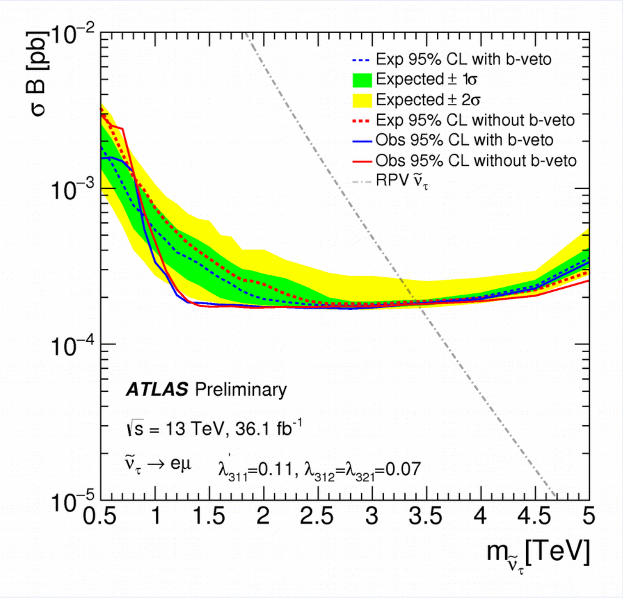


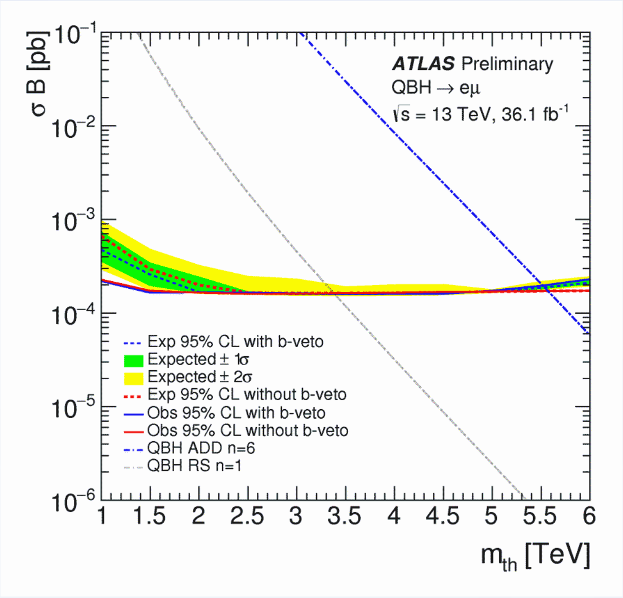
High-mass di-lepton search

arXiv:1607.08079 ...

Z' / $\tilde{\nu}_\tau$ / QBH → eμ / eτ / μτ







Model	Expected Limit [TeV]			Observed Limit [TeV]		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
Z'	3.2	2.7	2.6	3.0	2.7	2.6
RPV SUSY $\tilde{\nu}_\tau$	2.5	2.1	2.0	2.3	2.2	1.9
QBH ADD $n = 6$	4.6	4.1	3.9	4.5	4.1	3.9
QBH RS $n = 1$	2.5	2.2	2.1	2.4	2.2	2.1

← arXiv:1607.08079
3.2 fb^{-1}

High-mass di-lepton search

Results for eτ and μτ channels NEW Publication

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